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VOLUME 38 FEBRUARY 1957 NUMBER 1

CONTENTS

PAPERS

GEODESY

Gravity Observations at Sea in USS *Conger*, Cruise III
G. Lynn Shurbet and J. Lamar Worzel 1

Improvements in Tidal Gravity Meters and Their Simultaneous Comparison
H.N. Clarkson and L. J. B. LaCoste 8

METEOROLOGY

Observed and Computed Radiation from First to Fourth Contact during a Total Solar Eclipse ..... Lyman J. Briggs 17

A Comparison of Some Approaches to the Diabatic Wind Profile ..... William P. Elliott 21

Estimation of the Heat-Transfer Coefficient Between Air and the Ground Surface
Ronald F. Scott 25

A Nomogram for Log-Normal Frequency Analysis ..... L. L. Weiss 33

Laboratory Investigation of Some Characteristics of the Eppley Pyrheliometer
Don Fuquay and Konrad Buettner 38

Intensity and Frequency of Severe Storms in the Gulf of Alaska
Edwin F. Danielsen, Wayne V. Burt, and Maurice Rattray, Jr. 44

OCEANOGRAPHY

An Electronic Sea-Wave Recorder ..... V. Narayana Rao 50

Application of the Solitary Wave Theory to Shoaling Oscillatory Waves
John G. Housley and Donald C. Taylor 56

Axial Slope of Sea Level in Chesapeake Bay ..... M. J. Pollak 62

Pseudo-Characteristics ..... John C. Freeman, Jr. and Ledolph Baer 65

HYDROLOGY

An Analysis of Surface Energy During the Ablation Season on Lemon Creek Glacier, Alaska ..... Richard C. Hubley 68

Accuracy of Determination of Stream Lengths from Topographic Maps
Marie Morisawa 86

SEISMOLOGY

Anisotropy in Rocks under Simple Compression ..... Don Tocher 89

TECTONOPHYSICS

A Treatment of Self-Gravitational Strains in the Earth ..... Wilmot R. McCutchen 95

VOLCANOLOGY, GEOCHEMISTRY, AND PETROLOGY

Radiation Damage in Zircon and Its Relation to Ages of Paleozoic Igneous Rocks in Northern New England and Adjacent Canada
Harold W. Fairbairn and Patrick M. Hurley 99

REPORT

HYDROLOGY

Report of the Committee on Snow, 1955–1956 ..... R. A. Work, Chairman 108

(CONTENTS—*Continued*)

DISCUSSIONS

HYDROLOGY

Report of the Committee on Snow, 1954–55: Louis Lliboutry 114

Forest-Cover Effects on Snowpack Accumulation and Melt, Central Sierra Snow Laboratory: J. E. Church and H. W. Anderson 116

REVIEWS, ABSTRACTS, AND BIBLIOGRAPHY

REVIEWS AND ABSTRACTS

Harold M. Mooney and W. W. Wetzel, The Potentials About a Point Electrode and Apparent Resistivity Curves for a Two-, Three-, and Four-Layer Earth, Irwin Roman 117

Charles Schuchert, Atlas of Paleographic Maps of North America, A. J. Eardley 118

Ernest E. Wahlstrom, Petrographic Mineralogy, George T. Faust 118

E. Wm. Heinrich, Microscopic Petrography, Earl Ingerson 119

Warren B. Hamilton, Geology of the Huntington Lake Area, Fresno County, California, George T. Faust 119

BIBLIOGRAPHY

General 119

Geodesy 119

Terrestrial Magnetism and Electricity 121

Meteorology 123

Oceanography 124

Hydrology 126

Volcanology, Geochemistry, and Petrology 127

Tectonophysics 128

NOTES AND PERSONALIA

Notes 129

Personalia 132

UNION, SECTION, AND COMMITTEE ACTIVITIES

Proceedings of Executive Committee Meeting, November 17, 1956
A. Nelson Sayre and Waldo E. Smith 135

General Secretary's Report ..... A. Nelson Sayre 135

Appendix 1—Report of Committee to Study AGU Membership Committee Organization ..... H. E. Landsberg, Chairman 140

Appendix 2—Report of the Committee on Audit for the Fiscal Year Ending June 30, 1956 ..... A. G. McNish, Chairman 142

Appendix 3—Report of Representative of the American Geophysical Union on the Board of Directors of the American Geological Institute ..... E. A. Eckhardt 144

Pacific Northwest Meeting Held in Seattle, November 8–9, 1956 144

North Central Regional Committee Organized 145

Meeting of Geophysical Society of Hawaii, December 31, 1956 145

SPECIAL ANNOUNCEMENTS

Thirty-Eighth Annual Meeting, Washington, D. C., April 29–May 1, 1957 145

Eleventh General Assembly of IUGG to be held in Toronto, Canada, September 3–14, 1957 145

Cards of Corporation Members ..... Following page 145

Transactions
American Geophysical Union

VOLUME 38 APRIL 1957 NUMBER 2

CONTENTS

PAPERS

GEODESY

The Observation Accuracy of High-Range Geodetic-Type Worden Gravimeters
William E. Bonini and George P. Woollard 147

Gravity and Isostasy in Central Quebec ..... M. J. S. Innes 156

METEOROLOGY

A Field Installation for Automatic Recording of Micro-environmental Gradients
Robert B. Platt 166

The Transport of Sand by Wind ..... Edwin F. Ford 171

TERRESTRIAL MAGNETISM AND ELECTRICITY

A New Model of Magnetic Storms and Aurorae ..... S. F. Singer 175

OCEANOGRAPHY

Classification of Daily Sea-Water Data ..... Susumu Tabata 191

HYDROLOGY

A Criterion for Selection of Length of Record for a Moving Arithmetic Mean for Hydrologic Data ..... Robert T. Beaumont 198

Minimum Water Yield from Small Agricultural Watersheds ..... Lloyd L. Harrold 201

Evaporation Study at Silver Lake in the Mojave Desert, California ..... Harry F. Blaney 209

Rainfall-Runoff Relation for Small Basins ..... J. F. Miller and J. L. H. Paulhus 216

Soviet Methods of Reporting and Displaying Results of Chemical Analyses of Natural Waters and Methods of Recognizing Oil-Field Waters: A Summary
George V. Chilingar 219

Moisture Movement in Porous Materials under Temperature Gradients
J. R. Philip and D. A. de Vries 222

A Correlation of the Characteristics of Great Storms ..... M. C. Boyer 233

VOLCANOLOGY, GEOCHEMISTRY, AND PETROLOGY

Heat Flow at Grass Valley, California ..... Sydney P. Clark, Jr. 239

TECTONOPHYSICS

A Hypothesis of Formation of Mountains and Continents
B. D. Aggarwala and Edward Saibel 245

REPORT

SEISMOLOGY

Progress Report, Seismological Laboratory California Institute of Technology, 1956
H. Benioff, B. Gutenberg, F. Press, and C. F. Richter 248

(CONTENTS—*Continued*)

DISCUSSIONS

METEOROLOGY

Mean Airflow and Heat Transport Patterns Generated by Wind Machines with Applications to Frost Protection: Arthur S. Leonard and George Allen Baker, Jr. 254

Some Comments on the Deacon Wind Profile: Masao Shiotani, and Ben Davidson and Morton L. Barad 257

HYDROLOGY

A Test of the Single- and Double-Ring Types of Infiltrometers: Leonard Schiff, and R. H. Burgy and J. N. Luthin 260

LETTER TO THE EDITOR

Authors' Comments on Discussions of "Heated Precipitation-Gage Intake Tube" F. C. Allen, R. E. Glover, W. U. Garstka, and H. M. Posz 262

REVIEWS, ABSTRACTS, AND BIBLIOGRAPHY

REVIEWS AND ABSTRACTS

Willard J. Pierson, Jr., Gerhard Neumann, and Richard W. James, Practical Methods for Observing and Forecasting Ocean Waves by Means of Wave Spectra and Statistics, C. L. Bretschneider 264

Sverre Petterssen, Weather Analysis and Forecasting, 2nd ed., vol. 1, Motion and Motion Systems, R. G. Fleagle 266

William G. Hoyt and Walter B. Langbein, Floods, Waldo E. Smith 267

Edward Rowe Snow, The Vengeful Sea, J. L. 268

Abstracts of the Papers Presented at the Pacific Northwest Regional Meeting, Seattle, Washington, November 8–9, 1956 268

BIBLIOGRAPHY

General 271

Geodesy 271

Terrestrial Magnetism and Electricity 272

Meteorology 274

Oceanography 275

Hydrology 276

Seismology 277

Volcanology, Geochemistry, and Petrology 277

Tectonophysics 278

NOTES AND PERSONALIA

Notes 279

Personalia 282

UNION, SECTION, AND COMMITTEE ACTIVITIES

Suggestions to Authors 284

SPECIAL ANNOUNCEMENTS

Eleventh General Assembly of IUGG to be held in Toronto, Canada, September 3–14, 1957. 287

Plans of the North Central Regional Group 287

Pacific Northwest Regional Meeting to be held in November, 1957 287

Meeting of the Pacific Southwest Region 287

Cards of Corporation Members ..... Following page 287

DIRECTORY OF MEMBERS

(Separately paginated)

Preface 1

Alphabetical List of Individual Members 3

Alphabetical List of Corporation Members 69

Geographical List of Members 70

List of Committees of the Union and of the Sections 88

List of Publications 89

Transactions
American Geophysical Union

VOLUME 38 JUNE 1957 NUMBER 3

CONTENTS

NINETEENTH AWARD OF THE WILLIAM BOWIE MEDAL

Citation ..... Beno Gutenberg 289
Presentation ..... Leason H. Adams 290
Response and Acceptance ..... Maurice Ewing 290

PAPERS

GEODESY

Gravity Observations at Sea in USS *Corsair* ..... J. Lamar Worzel and G. Lynn Shurbet 292
Accuracy of Gravimetrically Computed Deflections of the Vertical .. William M. Kaula 297

TERRESTRIAL MAGNETISM AND ELECTRICITY

Extrapolation of Geomagnetic Field Components Along a Radius from the Center of the Earth ..... A. J. Zmuda 306

METEOROLOGY

Sky Temperatures in the Imperial Valley of California
C. F. Kelly, T. E. Bond, and N. R. Ittner 308

OCEANOGRAPHY

Photography of Submerged Vertical Structures ..... Raymond F. McAllister 314
The Effects of Cable Design on the Accuracy of the GEK
John A. Knauss and Joseph L. Reid 320

HYDROLOGY

Utilizing the Decomposition of Organic Residues to Increase Infiltration Rates in Water Spreading ..... Curtis E. Johnson 326
The Effect of Nonrepresentative Sampling on Linear Regressions as Applied to Runoff
W. D. Potter 333
Areal Representativeness of Point Rainfall ..... F. A. Huff and J. C. Neill 341
Perched Water Tables under an Artificial Ground-Water Recharge System
Warren A. Hall 346

SEISMOLOGY

Pacific and 'Mediterranean' Earthquake Mechanisms ..... A. R. Ritsema 349
A Case Study Bearing on the Origin and Propagation of 2- to 6-Second Microseisms
William L. Donn 354

VOLCANOLOGY, GEOCHEMISTRY, AND PETROLOGY

Isotopic Ages of Zircon from Granites and Pegmatites
G. R. Tilton, G. L. Davis, G. W. Wetherill, and L. T. Aldrich 360

TECTONOPHYSICS

Gravity Cross Section of the Coast Range of Venezuela ..... Raymond J. Smith 372

(CONTENTS—*Continued*)

REPORT

HYDROLOGY

Report of the Committee on Runoff, 1955–1956 ..... Ven T. Chow, Chairman 379

REVIEWS, ABSTRACTS, AND BIBLIOGRAPHY

REVIEWS AND ABSTRACTS

Abstracts of the Papers Presented at the Thirty-Eighth Annual Meeting, Washington, D. C., April 29–May 2, 1957 385

Abstracts of the Papers Presented at the Pacific Southwest Regional Meeting, Sacramento, California, February 14–15, 1957 414

BIBLIOGRAPHY

General 421
Geodesy 421
Terrestrial Magnetism and Electricity 423
Meteorology 425
Oceanography 426
Hydrology 427
Seismology 428
Volcanology, Geochemistry, and Petrology 430
Tectonophysics 433

NOTES AND PERSONALIA

Notes 433
Personalia 436

UNION, SECTION, AND COMMITTEE ACTIVITIES

THIRTY-EIGHTH ANNUAL MEETING (1957)

Smoker 438
Evening Session 438
Minutes, General Assembly ..... A. Nelson Sayre and Waldo E. Smith 438
Report of the General Secretary ..... A. Nelson Sayre 438
Thirty-Ninth Annual Meeting 439
Report of the Committee on Resolutions 439
New and Unfinished Business 439
Minutes of the Sections 439
Appendix A—Geodesy ..... Frank L. Culley, Secretary 439
Appendix B—Seismology ..... J. A. Peoples, Jr., Secretary 440
Appendix C—Meteorology ..... Woodrow C. Jacobs, Secretary 441
Appendix D—Terrestrial Magnetism and Electricity ..... Robert E. Gebhardt, Secretary 443
Appendix E—Oceanography ..... Donald W. Pritchard, Secretary 444
Appendix F—Volcanology, Geochemistry, and Petrology ..... L. T. Aldrich, Secretary 445
Appendix G—Hydrology ..... Ralph N. Wilson, Secretary 446
Appendix H—Tectonophysics ..... Benjamin F. Howell, Jr., Secretary 447
Russian Translation Project 447
Plans for Reprinting Out-of-Print *Transactions* 447
Meetings of the Geophysical Society of Hawaii 448
Activities of Pacific Southwest Region, AGU 448

SPECIAL ANNOUNCEMENTS

Translation of Russian scientific literature 448
Eleventh General Assembly of IUGG to be held in Toronto, Canada, September 3–14, 1957 448
Pacific Northwest Regional Meeting 448
Plans of the North Central Regional Group 448
Pacific Southwest Regional Meeting 448
Thirty-Ninth Annual Meeting 448

Cards of Corporation Members ..... Following page 448

Transactions
American Geophysical Union

VOLUME 38 AUGUST 1957 NUMBER 4

CONTENTS

Greetings to the Eleventh General Assembly of IUGG 449
Salute to the International Geophysical Year 449

PAPERS

GENERAL

Some Preparations for the International Geophysical Year Earth Satellite Program
Homer E. Newell, Jr. 450

GEODESY

Some Comments on the Results Obtained with the Cambridge Pendulum Apparatus in North America ..... R. L. G. Gilbert 457
Discussion: G. D. Garland 461

METEOROLOGY

Apparent Diurnal Variations of Arctic Stratospheric Temperatures ..... Arthur D. Belmont 462
Meteorological Measurements from a Minimum Satellite Vehicle ..... S. Fred Singer 469

OCEANOGRAPHY

The Method of Wave Derivatives ..... John C. Freeman, Jr., and Ledolph Baer 483
Propagation and Dissipation of Long Internal Waves ..... Maurice Rattray, Jr. 495

HYDROLOGY

Water Supply and Drainage in Semi-Arid Countries ..... Alfred Loehnberg 501
Some Problems in Non-Artesian Ground-Water Flow ..... P. Wilh. Werner 511
The Statistical Treatment of Flood Flows ..... P. A. P. Moran 519
Relation of Potential Evapotranspiration to Environment and Kind of Plant
W. O. Drinkwater and B. E. Janes 524

SEISMOLOGY

Shadow Zones, Travel Times, and Energies of Longitudinal Seismic Waves in the Presence of an Asthenosphere Low-Velocity Layer ..... Marcus Båth 529

VOLCANOLOGY, GEOCHEMISTRY, AND PETROLOGY

The Reproducibility of A^{40}/K^{40} Age Determinations
H. Baadsgaard, S. S. Goldich, A. O. Nier, and J. H. Hoffman 539

Symposium on Geochronology

Some Recent Harwell Analytical Work on Geochronology
R. K. Webster, J. W. Morgan, and A. A. Smales 543
Investigations in A^{40}/K^{40} Dating ..... S. S. Goldich, H. Baadsgaard, and A. O. Nier 547
Anomalous Leads from the Upper Great Lakes Region of Ontario
R. M. Farquhar and R. D. Russell 552
Isotopic Analyses of Leads from Broken Hill, Australia
R. D. Russell and R. M. Farquhar 557
Spectrographic Analyses ..... J. E. Hawley 564
Reinterpretation of the Uranium-Helium Ages of Iron Meteorites
E. J. Öpik and S. F. Singer 566

TECTONOPHYSICS

Polymorphism in the Earth's Mantle ..... W. T. Holser and C. J. Schneer 569

TECHNICAL NOTE

Deflections of the Vertical in New Britain ..... William M. Kaula 578

(CONTENTS—*Continued*)

DISCUSSIONS

GEODESY

A New Determination of the Figure of the Earth from Arcs
W. A. Heiskanen, and Bernard Chovitz and Irene Fischer 579

HYDROLOGY

On Estimating Streamflow into Tidal Estuary
D. W. Pritchard, and David K. Todd and Leung-ku Lau 581

OCEANOGRAPHY

Evidence for a Critical Wind Velocity for Air-Sea Boundary Processes, *and* Change in the Relationship Between Wind and Surface Water Movement at Higher Wind Speeds
Hugo Mandelbaum, and A. L. Lawford and V. F. C. Veley 584

REVIEWS, ABSTRACTS, AND BIBLIOGRAPHY

REVIEWS AND ABSTRACTS

Walter J. Saucier, Principles of Meteorological Analysis . . . . . Jay S. Winston 587

BIBLIOGRAPHY

General 587
Geodesy 588
Terrestrial Magnetism and Electricity 589
Meteorology 590
Oceanography 591
Hydrology 592
Seismology 593
Volcanology, Geochemistry, and Petrology 593

NOTES AND PERSONALIA

Notes 594
Personalia 596

UNION, SECTION, AND COMMITTEE ACTIVITIES

Minutes of Executive Committee Meeting, April 28 and May 1, 1957
A. Nelson Sayre and Waldo E. Smith 599

General Secretary's Report . . . . . A. Nelson Sayre 599

Appendix 1—Report of the Committee on International Participation
J. Wallace Joyce 604

Appendix 2—Report of the Committee on Budget for the Fiscal Year Ending June 30, 1958 . . . . . John C. Reed, Chairman 606

Appendix 3—Report of the Committee on Statutes and By-Laws to the Executive Committee . . . . . K. Hilding Beij, Chairman 608

Appendix 4—Status Report of the AGU Membership Committee . . . Earl G. Droessler 608

SPECIAL ANNOUNCEMENTS

Notice of Intent to Change the By-Laws 610
Meeting of Pacific Northwest Regional Group 610
Meeting with the AAAS in Indianapolis 610
Pacific Southwest Regional Meeting in Pasadena, February 6–7, 1958 610
Thirty-Ninth Annual Meeting 610
IGY Bulletin No. 1 611
Antarctic Program 612
Arctic Drift Ice Station Program 617
The Earth Satellite Program 619
Status Report: Seismology, Gravity, and Longitude & Latitude 623
Reports from Other Countries 625
IGY Bulletin No. 2 627
Status Report: Meteorology, Oceanography, and Glaciology 627
World Days During the IGY 631
Rockets and Satellites: Radio Tracking System 633
CSAGI and the IGY 637
Antarctic Notes 640
Corporation Members 642

Transactions
American Geophysical Union

VOLUME 38 OCTOBER 1957 NUMBER 5

CONTENTS

PAPERS

GENERAL

Radiocarbon Evidence on the Dilution of Atmospheric and Oceanic Carbon by Carbon from Fossil Fuels ..... H. R. Brannon, Jr., A. C. Daughtry, D. Perry, W. W. Whitaker, and M. Williams 643

GEODESY

Surveying by Occultations ..... S. W. Henriksen, S. H. Genatt, M. Q. Marchant, and C. D. Batchlor 651

METEOROLOGY

A Note on the Precision of Estimation of Missing Precipitation Data ..... James E. McDonald 657

OCEANOGRAPHY

On the Damping of Gravity Waves Over a Permeable Sea Bed ..... R. O. Reid and K. Kajiura 662

Wave Measurements along the California Coast ..... R. L. Wiegel and J. Kukk 667

On the Offshore Distribution of Tide and Tidal Current ..... Maurice Rattray, Jr. 675

Direct Shear Stresses and Air Velocity Profiles on a Mechanical Wave Boundary ..... G. H. Moore and A. D. K. Laird 681

Flooded Quarries for Experimental Work ..... Milton S. Rutstein 688

HYDROLOGY

A Probe for Measurement of Thermal Conductivity of Frozen Soils in Place ..... Arthur H. Lachenbruch 691

A Method of Forecasting Stages on Flat Rivers ..... William E. Ray and Herman F. Mondschein 698

Relationship of Unmeasured Sediment Discharge to Mean Velocity ..... B. R. Colby 708

Global Distribution of the Annual Range in Soil Temperature ..... Jen-hu Chang 718

Hydrologic Investigations at Hanford ..... J. R. Raymond and W. H. Bierschenk 724

Underdrainage into Ditches in Soil Overlying an Impervious Substratum ..... Hitoshi Fukuda 730

Evaporation Suppression from Water Surfaces ..... W. J. Roberts 740

The Thickness of Lemon Creek Glacier, Alaska, as Determined by Gravity Measurements ..... E. Thiel, E. LaChapelle, and J. Behrendt 745

SEISMOLOGY

The 'Boundary' of the Earth's Inner Core ..... B. Gutenberg 750

VOLCANOLOGY, GEOCHEMISTRY, AND PETROLOGY

A Method to Determine the Isotopic Ratio of Thorium^{232} to Thorium^{230} in Minerals ..... Elizabeth Rona 754

DISCUSSIONS

OCEANOGRAPHY

Properties of Shoaling Waves by Theory and Experiment: R. L. Wiegel, P. Danel, and Peter S. Eagleson 760

(CONTENTS—*Continued*)

GEODESY

A Statistical Analysis of Hiran Measurements: George R. Woodring and Joseph L. Stearn.. 763

HYDROLOGY

A Floating Lysimeter and its Evaporation Recorder: L. L. Harrold and F. R. Dreibelbis, D. B. Krimgold, and K. M. King, C. B. Tanner, and V. E. Suomi 765

Application of the Modified Einstein Procedure for Computation of Total Sediment Load: Emmett M. Laursen, Lloyd C. Fowler, and K. B. Schroeder and C. H. Hembree..... 768

Effect of Various Hydro-Climatic Factors on Snowmelt Runoff: Willard M. Snyder, Donald W. Kuehl, and Victor A. Koelzer and Perry M. Ford 773

LETTERS TO THE EDITOR

Comments on a Review by C. L. Bretschneider of "Practical Methods for Observing and Forecasting Ocean Waves by Means of Wave Spectra and Statistics," U. S. Navy Hydrographic Office Pub. No. 603, by W. J. Pierson, Jr., G. Neumann, and R. W. James.....W. H. Munk, and Gerhard Neumann and Willard J. Pierson, Jr. 778

Use of a Taylor Series as an Interpolation Formula with Magnetic Intensity Values
Alfred J. Zmuda 781

Remarks on the Analytical Derivation of the Darcy Equation.....John R. Philip 782

An IGY Bibliography.....John Sherrod 784

REVIEWS, ABSTRACTS, AND BIBLIOGRAPHY

REVIEWS AND ABSTRACTS

Joseph Murdoch and Robert W. Webb, Minerals of California, George T. Faust 785

Oceanographic Observations of the Pacific, J. L. 785

BIBLIOGRAPHY

General 785

Geodesy 786

Terrestrial Magnetism and Electricity 786

Meteorology 788

Oceanography 789

Hydrology 791

Seismology 792

Volcanology, Geochemistry, and Petrology 793

Tectonophysics 793

NOTES AND PERSONALIA

Notes 793

Personalia 795

SPECIAL ANNOUNCEMENTS

Meeting of Pacific Northwest Regional Group 797

Pacific Southwest Regional Meeting in Pasadena, February 6–7, 1958 797

Thirty-Ninth Annual Meeting to be Held in Washington, D. C., May 5–7, 1958 797

Note to Associate Members 798

(CONTENTS—*Continued*)

IGY Bulletin No. 3 799
Status Report: The Upper Atmosphere Program 799
Solar Activity Program 800
Cosmic-Ray Program 801
Geomagnetism Program 805
Ionospheric Physics Program 808
Aurora and Airglow Program 811
Rocket Program 812
IGY Bulletin No. 4 815
Current Sunspot Numbers 815
The IGY Research Rocket Program 818
IGY Antarctic Weather Central 821
Arctic Program 824
Corporation Members ..... Following page 830

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INDEX TO VOLUME 38—1957

INDEX OF NAMES

* Indicates obituary

Abramson, H. N., 849
Ackermann, W. C., 925
Adams, L. H., 290
Adler*, L., 983
Aggarwala, B. D., 245
Aldrich, L. T., 360, 385, 409, 412
Allen, F. C., 262
Allen, R. A., 385
Alper, A. M., 385
Althouse*, I. H., 283
Anderson, H. W., 116, 414, 921
Angell, J. K., 385
Arle, H. F., 414
Aronovici, V. S., 415
Atkinson, B. M., 411

Baadsgaard, H., 385, 392, 539, 547
Backus*, O. J., 437
Baer, L., 65, 483
Baker, G. A., Jr., 254
Balsley, J. R., 386
Bangs*, E. F., 597
Barad, M. L., 257, 386
Barker, F. B., 386
Barnes, C. A., 268
Batchlor, C. D., 394
Bate, G. L., 386
Bates, C. C., 386
Bates, H. F., 269
Båth, M., 529
Bauer, J. R., 400
Bauer, S. J., 387
Bazan, F., 392
Bean, R. T., 415
Beaumont, R. T., 198
Becker, C. H., 415
Beetem, W. A., 406
Behrendt, J., 745
Beij, K. H., 608
Belmont, A. D., 462
Belote, E. S., 387
Benedict, P. C., 897
Benioff, H., 248
Bennett, G. D., 406
Berckhemer, H., 407
Bierschenk, W. H., 270, 724
Blackadar, A. K., 387, 402
Blaney, H. F., 209, 415
Bock, P., 387
Bond, T. E., 308
Bonini, W. E., 147
Born, R. H., 420
Bowser, C. W., 415
Boyer, M. C., 233
Braham, R. R., Jr., 387
Brannon, H. R., Jr., 387, 643
Bretschneider, C. L., 264, 387, 778
Briggs, L. J., 17
Broecker, W. S., 388
Brown, G. L., 835
Brown, H., 388
Brown, J. S., 390
Brown, R. E., 269
Brownlow, A. H., 388
Bryant, G. T., 391
Buajitti, K., 387
Buddington, A. F., 386
Buettner, K., 38
Bunce, E. T., 395
Burgy, R. H., 260
Burt, W. V., 44
Bybee*, H. P., 437
Bycroft, G. N., 928

Cartwright, D. E., 864
Chang, J., 718
Chayes, F., 389
Chernosky, E. J., 389
Chew, F., 389
Chilingar, G. V., 219
Chiu, Wan-Cheng, 389
Chovitz, B., 579
Chow, V. T., 379, 962, 963
Church, J. E., 116
Clark, S. P., Jr., 239, 931
Clarkson, H. N., 8
Clendenen, F. B., 416
Colby, B. R., 708
Coldwell, A. E., 908
Comstock, D. F., 411
Cormier, R. F., 396
Corn, H. M., 960
Cox, Allan, 389
Cramer, H. E., 389
Cremer, H. J., 416
Crutcher, H. L., 389
Curtis, R. C., 390

Damon, P. E., 390, 945
Danel, P., 760
Danielsen, E. F., 44
Daughtry, A. C., 387, 643
Davidson, B., 257
Davis, G. H., 416
Davis, G. L., 360, 409, 412
de Bremaecker, J. Cl., 960
Decker, F. W., 269
Decker, J. P., 416
de Golyer*, E. L., 133
Dellert, G. T., Jr., 390
Deppermann*, C. E., 597
de Vries, D. A., 222
Dickson, C. R., 408
Dietz, F. T., 395
Donn, W. L., 354
Drake, C. L., 401
Dreibelbis, F. R., 765
Drinkwater, W. O., 524
Droessler, E. G., 608
Dunn, C. R., 390

Eagleson, P. S., 760
Eardley, A. J., 118
Eckhardt, E. A., 144
Ecklemann, F. D., 390
Edmonston*, A. D., 437
Elliott, E. W., 420
Elliott, W. P., 21
Ellis, J. O., 385
Ewing, J. I., 390
Ewing, M., 290

Fairbairn, H. W., 396, 939
Farquhar, R. M., 390, 552, 557
Farrell, J. P., 963
Faust, G. T., 118, 119, 785
Ferber, G. J., 391
Ferraes, S. G., 391
Fischer, I., 579
Fisher, R. L., 400
Fleagle, R. G., 266, 391
Ford, E. F., 171
Ford, P. M., 773
Fosberg, M. A., 397
Fougere, P. F., 400
Fowler, L. C., 768
Freeman, J. C., Jr., 65, 483
Friedman, D. G., 400
Fukuda, H., 730
Fultz, D., 403
Fundali, R. F., 391
Fuquay, D., 38
Fuquay, J. J., 269

Garcia-Rodriguez*, R., 597
Garland, G. D., 461
Garstka, W. U., 262
Genatt, S. H., 394
Gerard, R. D., 388
Geyer, J. C., 387, 391
Gilbert, R. L. G., 457
Giletti, B. J., 392
Glover, R. E., 262
Glymph, L. M., Jr., 903
Goguel, J., 970
Goldberg, P. A., 269
Goldich, S. S., 385, 392, 539, 547
Goldin, A. S., 407
Gottschalk, L. C., 885

Green, J. H., 418
Grover[a], N. C., 134
Gunn, Ross, 392
Gutenberg, B., 248, 289, 392, 393, 750

Hafer, L. F., 395
Hagee, G. R., 407
Hall, W. A., 346
Halstead, M. H., 393
Hamaguchi, H., 393
Hamilton, W. B., 119
Harney, P. J., 393
Harris, M. F., 393
Harris, R. L., 393
Harrison, A. E., 269
Harrison, J. C., 835
Harrold, L. L., 201, 765
Hawley, J. E., 564
Heaps, H. S., 394
Heezen, B. C., 388, 394
Heinrich, E. W., 119
Heiskanen, W. A., 394, 579, 841
Hembree, C. H., 768
Henderson, R. G., 394
Hennion, J. F., 390
Henriksen, S. W., 394
Heppner, J. P., 394
Hersey, J. B., 395
Heslop[a], P. L., 597
Hess, H. H., 395
Hoecker, W. H., Jr., 395
Hoehne, W. E., 395
Hoffman, J. H., 539
Hollingsworth, B. J., 395
Holloway, L., 395
Holmes, D. W., 395
Holmes, J. C., 397
Holser, W. T., 569
Hood, D. W., 396
Hoover, R. A., 396
Housley, J. G., 56
Howe, G. M., 400
Hoyt, W. G., 267
Hubert, W. E., 396
Hubley[a], R. C., 68, 983
Huff, F. A., 341, 960
Hughes, Darrell S., 396
Huizenga, J. R., 386
Hurley, P. M., 396, 939
Hynek, J. A., 396

Ingerson, E., 119
Innes, M. J. S., 156
Ittner, N. R., 308

Jacob, C. E., 417
Jacobs, J. A., 401
Jaeger, J. C., 971
Jagsich[a], J., 597
James, R. W., 264, 778
Janes, B. E., 524
Jardetzky, W. S., 397
Jiranek, M. V., 417
Johnson, C. E., 326, 419
Johnson, C. Y., 397
Jordan, J. V., 397
Joyce, J. W., 604

Kajiura, K., 662
Kao, S.-K., 397, 831
Kaufman, W. J., 269
Kaula, W. M., 297, 578
Kazmann, R. G., 417
Kellogg[a], R. W., 796
Kelly, C. F., 308
King, K. M., 765
Klein, G., 269
Klein, W. H., 397
Knauss, J. A., 320
Knopoff, L., 397
Koelzer, V. A., 773
Kouvo, O., 398
Kramer[a], H., 796
Kraus[a], P. S., 597
Krimgold, D. B., 765
Kuehl, D. W., 773
Kukk, J., 667
Kulp, J. L., 390, 945

LaChapelle, E., 745
Lachenbruch, A. H., 691
LcCoste, L. J. B., 8
Laird, A. D. K., 681
Lamb[a], G. B., 283
Landsberg, H. E., 140
Lane[a], A. A., 796
Langbein, W. B., 267
Langleben, M. P., 398
Langmuir[a], I., 796
Larsen, L. H., 398
Lau, L., 581
Laursen, E. M., 768
Lawford, A. L., 584
Lee, O. S., 412
Lemmon, P. E., 270
Leonard, A. S., 254
Lewis, G. C., 397
Lewis, M. L., 404
Linsley, R. K., 398
List, R. J., 398
Lliboutry, L., 114
Loehnberg, A., 501
Lofgren, B. E., 417
Long, G. L., 419, 879
Louderback[a], G. D., 283
Ludzack, F. J., 407
Luthin, J. N., 260

MacCarthy, G. R., 398
Mandelbaum, H., 584, 867
Mann, J. F., Jr., 418
Manos, Nicholas E., 398, 399
Maple, E., 399
Marchant, M. G., 394
Marks, W., 399
Marshall, R. R., 399
Masterson, J. E., 399
Maxey, G. B., 412
Maytin, I. L., 270
McAllister, R. F., 314
McClay, J. F., 400
McClure, C. R., 415
McCrosky, R. E., 400
McCutchen, W. R., 970
McDonald, J. E., 657
McKinney, C. R., 388
McNish, A. G., 142
McQueen, R. G., 396
Meadows, E. B., 397
Menard, H. W., 400
Meredith, L. H., 394
Meyer, H. I., 395
Meyer, J. H., 400
Miller, A. R., 400
Miller, J. F., 216
Miller, R. G., 400
Mitchell[a], H. C., 134
Mockus, V., 418
Mondschein, H. F., 698
Mooney, H. M., 117
Moore, C. B., 411
Moore, G. H., 681
Moran, P. A. P., 519
Morgan[a], H. R., 597
Morgan, J. W., 543
Morisawa, M., 86
Munk, W., 400, 401, 407, 778
Murdoch, J., 785

Nafe, J. E., 401, 407
Narayana Rao, V., 50
Nash, J. E., 963
Neill, J. C., 341, 960
Neumann, G., 264, 778
Newell, H. E., Jr., 401, 450
Nier, A. O. C., 385, 392, 539, 547
Nomicos, G. N., 420

Obayashi, T., 401
Officer, C. B., 390
O'Keefe, J. A., 401
Öpik, E. J., 566
Orcutt, R. G., 269

Panofsky, H. A., 402
Park, K., 396
Parker, F. L., 402
Paulhus, J. L. H., 216
Pearson, G. L., 270
Perry, D., 387, 643
Pettersen, S., 266, 402
Pharo, L. C., 410
Philip, J. R., 222, 782
Phillips, B. B., 392
Pierson, W. J., Jr., 264, 402, 778
Pinson, W. H., 396
Platt, R. B., 166
Poland, J. F., 418
Poldervaart, A., 385, 393
Pollak, M. J., 62
Posz, H. M., 262
Potter, W. D., 333, 402
Press, F., 248, 402
Pritchard, D. W., 403, 581

Pritchett[a], J. W., 598
Prophet, D. T., 418

Quenneville, L. R., 391

Rabbitt[a], J. C., 598
Rapp, G. R., Jr., 403
Rattray, M., Jr., 44, 270, 495, 675
Ray, W. E., 698
Raymond, J. R., 270, 724
Record, F. A., 403
Reed, G. W., 393
Reed, J. C., 606
Reid, J. L., 320
Reid, R. O., 662
Reinhart, K. G., 403
Reiss, G. W., 391
Richman, R. L., 393
Richter, C. F., 248, 415
Riehl, H., 403
Riggs, L. P., 410
Ritsema, A. R., 349
Roberts, W. J., 403, 740
Robertson, E. C., 971
Robinson, T. W., 418
Roman, I., 117
Rona, E., 404, 754
Rosinski, J., 857
Ross, C. S., 404
Ross, J. E. R., 404
Ross, M. D., 404
Rossby[a], C.-G., 796
Rowe, R. R., 419, 879
Royce, T. C., 419, 879
Ruggles, F. H., 406
Ruskin, R. E., 404
Russell, R. D., 390, 552, 557
Rutstein, M. S., 688

Sahama, T. G., 407
Saibel, E., 245
Sanders, F., 405
Sartor, J. D., 405
Sassman, J. M., 385
Saucier, W. J., 587
Sayre, A. N., 135, 599
Schell, I. I., 405
Schiff, L., 260, 419
Schilling, G. F., 400, 412
Schneer, C. J., 569
Schooley, A. H., 405
Schroeder, K. B., 768
Schuchert, C., 118
Scott, R. C., 386
Scott, R. F., 25
Setter, L. R., 405
Shafer, R. J., 406
Shepard[a], E. R., 983
Sherman[a], Leon, 437
Sherrod, J., 784
Shinners, W. W., 406
Shiotani, M., 257
Shirley, J. A., 406
Shneiderov, A. J., 406
Shubert, G. L., 1
Shulits, Sam, 406
Shurbet, G. L., 292
Simpson, E. S., 406
Singer, S. F., 175, 406, 469, 566
Skudrzyk, E., 410
Smagorinsky, J., 406
Smales, A. A., 543
Smith, D. D., 413, 889
Smith, J. B., 396
Smith, J. V., 407
Smith, R. J., 372
Smith, W. E., 135, 267, 599, 984
Smith, Warren, 407
Snodgrass, F., 400, 407
Snow, E. R., 268
Snyder, W. M., 773
Soske, J. L., 415
Spencer, E. W., 407
Spiegel, Z., 419
Spiess, F. N., 835
Starke, P. P., 413
Stearn, J. L., 763
Stolarik, J. D., 394
Störmer[a], C., 983
Strahler, A. N., 913, 954
Straub, C. P., 405, 407
Suomi, V. E., 407, 765
Sutton, G. H., 407
Sverdrup[a], H. U., 796

Tabata, S., 191
Takahashi, T., 408
Talcott, M. G., 413
Tanner, C. B., 765
Taylor, D. C., 56
Taylor, E. A., 408
Thiel, E., 745
Thom, H. C. S., 408
Thomas, R. G., 420
Thompson, A. H., 408
Thompson, C. B., 420
Thompson, G. A., 408
Thompson, Jack C., 409
Thompson, John C., 420
Thompson, L. G. D., 409
Thompson, P. D., 409
Thornton, C. P., 410
Thurston, W. R., 395
Tilton, G. R., 360, 409
Tinney, E. R., 270
Tocher, D., 89
Todd, D. K., 581
Trauger[a], G. W., 797
Turekian, K. K., 410
Turkevich, A., 393
Tuttle, O. F., 410, 413
Twenhofel[a], W. H., 598

Urban, V. D., 410
Urick, R. J., 410

Vanoni, V. A., 420
Vaughan, H. C., 410
Veley, V. F. C., 584
Vestine, E. H., 411
Vinyard, H. R., 269
Vonnegut, B., 411

Wagner, A. J., 411
Wahlstrom, E. E., 118
Walton, M., 412
Wanner[a], E., 134
Watanabe, K., 410
Webb, R. W., 785
Webster, R. K., 543
Weeks, W. F., 412
Weiss, L. L., 33, 962
Werner, P. W., 511
Wetherill, G. W., 360, 409, 412
Wetzel, W. W., 117
Wexler, H., 954
Whipple, F. L., 396, 412
Whitaker, W. W., 387, 643
White, W. A., 412
Wiegel, R. L., 667, 760
Wien, Janet D., 416
Williams, A. J., 864
Williams, M., 387, 643
Wilm, H. G., 413
Wilson, H. D., Jr., 421
Winston, J. S., 587
Wischmeier, W. H., 413, 889
Wood, J. A., Jr., 413
Woodring, G. R., 763
Woollard, G. P., 147
Work, R. A., 108
Worzel, J. L., 1, 292, 413
Wyett, R. E., 413
Wyllie, P. J., 413
Wyrick, R. F., 395

Zmuda, A. J., 306, 414, 781

INDEX OF SUBJECTS

AAAS, Meeting, 610
A^{40}/K^{40} age determinations, reproducibility, 539
A^{40}/K^{40} dating of rocks, 385, 392, 547
Ablation season, analysis of surface energy on Lemon Creek Glacier, Alaska, 68
Abstracts of papers
  Pacific Northwest Regional Meeting, 268
  Pacific Southwest Regional Meeting, 414
  38th annual meeting, 385
Aerograph data from an L-20 aircraft, 393

Aerograph for humidity-temperature soundings from aircraft, 404
Age determinations, A^{40}/K^{40}, 539
Age measurements on rocks north of Lake Huron, 412
Ages, alpha-helium, of pegmatite zircons, 390
Age, comparison of A^{40}/K^{40} and Sr^{87}/Rb^{87}, on biotite, 396
Ages of minerals, measurement, 385
Ages, uranium-helium in iron meteorites, 566
Airflow and heat transport patterns generated by wind machines, 254
Airglow and aurora program, IGY, 811
Airglow measurements during the IGY, 994
Air particles, oscillation of, effects on trajectory in the atmosphere, 397
Air pollution, effect on the initiation of rain, 392
Air pollution, meteorlogy, 398
Air-sea boundary processes, evidence for a critical velocity, 584
Air velocity profiles and direct shear stresses on a mechanical wave boundary, 681
Alaska
  analysis of surface energy during the ablation season on Lemon Creek Glacier, 68
  intensity and frequency of storms in Gulf of, 44
  sub-audio frequency geomagnetic fluctuations, 399
  thickness of Lemon Creek Glacier determined by gravity measurements, 745
Altitude distribution of nightglow emissions, rocket measurements at White Sands Proving Ground, 394
American Geological Institute, report on board of directors, 144
Anomalies in magnetic and gravity field, downward continuation, 394
Antarctic notes, IGY, 640
Antarctic program, IGY, 612
Antarctic weather central, IGY, 821
Apatite, abundance and distribution of uranium and thorium in, 939
Aperiodic pole shift, possibility, 397
Appointments, committee, 600, 987
Aquifers, fractured-rock, development and management, 418
Arcs, use in new determination of figure of Earth, 579
Arctic
  diurnal variations of stratospheric temperatures, 462
  drift ice station program, IGY, 617
  program, IGY, 824
  rockoon firings, IGY, 998
  submarine ridges, IGY, 1016
Areal representativeness of point rainfall, 341
Arithmetic mean for hydrologic data, criterion for length of record, 198
Arizona, full development of water resources, 419
Arizona, water-yield improvement, 413
Asia, cyclone distributions along east coast, 389
Associate members, note to, 798
Asthenosphere low-velocity layer, shadow zones, travel times, and energies of longitudinal seismic waves, 529
Atlantic Ocean, deep water circulation, 388
Atlantic Ocean surface water, C^{14}/C^{12} ratio variations, 388
Atmospheric and oceanic carbon, radiocarbon evidence on dilution, 387, 643
Atmospheric dynamo-action and magnetic storms, sudden commencements, 401
Atmospheric flow patterns, large-scale, uncertainty of initial state, 409
Atmosphere, upper, data expected from the IGY satellite tracking program, 412
Atmosphere, upper, report of the committee, 954
Audit, fiscal year ending June 30, 1956, 142
Aurora and airglow program, IGY, 811
Aurorae, new model of magnetic storms, 175
Australia, isotopic analyses of leads from Broken Hill, 557
Authors, suggestions, 284

Barium and uranium contents of meteorites, 393
Basic rocks, density at very high pressures, 396
Belgian Congo, volcanic eruption, 960
Bibliography
  General, 119, 271, 421, 587, 785, 971
  Geodesy, 119, 271, 421, 588, 786, 972
  Hydrology, 126, 276, 427, 592, 791, 977
  IGY, 784
  Meteorology, 123, 274, 425, 590, 788, 974
  Oceanography, 124, 275, 426, 591, 789, 975
  Seismology, 277, 428, 593, 792, 977
  Tectonophysics, 128, 278, 433, 793, 978
  Terrestrial magnetism and electricity, 121, 272, 423, 589, 786, 973
  Volcanology, geochemistry, and petrology, 127, 277, 430, 593, 793, 978
Bicarbonate ion as a source of carbon for marine plants, its oceanographic significance, 396
Biotite, comparison of A^{40}/K^{40} and Sr^{87}/Rb^{87} ages, 396
'Boundary' of the Earth's inner core, 750
Bowie Medal, ninteenth award, 289
Brines, possible mechanism for concentration, 412
Budget, report of the committee, 606
By-laws, notice of intent to change, 610

C^{14}/C^{12} ratio variations of Atlantic ocean surface water, 388
Cable design, effects on accuracy of GEK, 320
Calibration of five small forested watersheds, 403
California
  evaporation study at Silver lake, Mojave desert, 209
  geology and ground-water hydrology of San Luis Obisbo County, 420
  geology of the Huntington Lake area, 119
  ground-water circulation in deep wells, San Joaquin Valley, 417
  ground water in the Sacramento Valley, 416
  ground-water resources, 415
  heat flow at Grass Valley, 239
  Imperial Valley sky temperatures, 308
  investigation of the predictability of the Kern River runoff to evaluate a precipitation-increasing program, 418
  minerals, 785
  northern, correlation of rainfall intensity and topography, 398
  subsidence in the Santa Clara Valley, 418
  two-second microseisma, 393

utilization of ground-water basins in Santa Barbara County, 421
wave measurements, 667
zircons of the Bald Rock batholith, 398
Cambridge pendulum apparatus, results in North America, 457
Canada, Fort Churchill, ion composition of the ionosphere, 397
Carbon for marine plants, bicarbonate ion as a source, its oceanographic significance, 396
Caribbean, eastern, seismic refraction measurements, 390
Central Sierra Snow Laboratory, forest-cover effects on snowpack, 116
Channel erosion, importance as a source of sediment, 913
Channels, open, eddy viscosities, 406
Characteristics of great storms, 233
Chemical analyses of natural waters, Soviet methods of reporting, 219
Chesapeake Bay, axial slope of sea level, 62
Chondritic meteorites, existence of groups, 388
Circulation, deep water, in Atlantic Ocean, 388
Circulation in a dishpan experiment with steady long waves and jet stream, 403
Circulation research program of the U. S. Weather Bureau, 406
Clipperton fracture zone in the northeastern equatorial Pacific, 400
Cloud droplets, force and electrical field between, in a uniform electrical field, 405
Coastal water levels of New England, effect of winds, 400
Columbia River estuary, effect of logging on the runoff of a nearby stream, 270
Columbus geoid, 394, 841
Compression, anistrophy in rocks, 89
Concentration of brines, possible mechanism, 412
Conductivity, thermal, probe for measurement of frozen soils in place, 691
Constant-volume balloon for high-altitude soundings, 395
Continents and mountains, hypothesis of formation, 245
Core, Earth's inner 'boundary,' 750
Cosmic-ray program, IGY, 801
Crevasse detector, four-electrode, theoretical investigations, 849
Critical wind velocity for air-sea boundary processes, 584
Crustal structure and deep-sea physiographic provinces, 394
Crustal structure from phase velocity of Rayleigh waves, 402
Crust thickness, discrepancies as calculated from seismic and gravity data, 392
CSAGI rocket and satellite conference, IGY, 1005
Cumulus clouds, observations of electrification, 411
Cyclone distributions, east coast of Asia, 389

Damping of gravity waves over a permeable sea bed, 662
Darcy equation, analytical derivation, 782
Dating, A^{40}/K^{40}, 385, 392, 547
Deacon wind profile, 257
Decomposition of organic residues, use to increase infiltration rates, 326
Deep-sea cores, significance of variations in the strontium content, 410
Deep-sea sediments, physical aspects, 407
Deflections of vertical, gravimetrically computed, 297
Deflections of the vertical in New Britain, 578
Diabatic wind profile, 21
Differentiation index as a tool for classifying the igneous rocks, 410
Diffusion field studies, 200-meter scale, 269
Diffusion measurement techniques used during Project Prairie Grass, 403
Directional spectrum of a wind-generated sea, 399, 402
Directory of members, following page 288
Discharges from ungaged catchments, frequency, 963
Disposal of radioactive waste on land, 395
Diurnal variations, Arctic stratospheric temperatures, 462
Diurnal wind-structure variations, 387
Drainage and water supply in semi-arid countries, 501

E-region winds responsible for the solar daily magnetic variation, seasonal variability, 411
Earth
'boundary' of inner core, 750
hearth hypothesis of the constitution, 406
radiative transfer in the mantle, 931
rotation, 401
satellite program, IGY, 619, 1007
satellites, scientific uses, 401
treatment of self-gravitational strains, 970
Earthquake mechanisms, Pacific and 'Mediterranean,' 349
Earthquake, Virginia, August 27, 1833, 398
Earth's core, extrapolation of geomagnetic field components to, 414
Earth's core, rigidity, and internal friction in the mantle, 402
Earth's figure, determination from arcs, 579
Einstein procedure, modified, for computation of sediment load, 768
Elastic solid, dependence of surface strain and internal stress upon irregularities, 394
Elasticity, fracture and flow, with engineering and geological applications, (review), 971
Electrical field between cloud droplets in a uniform electrical field, 405
Electrification of cumulus clouds, 411
Electromagnetic activity, natural, low audio and subaudio frequencies, 269
Electronic sea-wave recorder, 50
Eleventh General Assembly of IUGG, 145, 287, 448, 449, 984
Energy, surface, analysis during the ablation season on Lemon Creek Glacier, Alaska, 68
Environmental gradients, field installation for automatic recording, 166
Epidote, abundance and distribution of uranium and thorium in, 939
Eppley pyrheliometer, characteristics, 38
Erosion
channel, importance as a source of sediment, 908
losses, kinetic energy of rainfall, 413
sheet and rill, affecting factors, 889

sheet, importance as a source of sediment, 903
symposium, 885
Estuaries, non-tidal drift, 403
Evaporation recorder and a floating lysimeter, 765
Evaporation study at Silver lake in the Mojave Desert, California, 209
Evaporation suppression from water surfaces, 403, 740
Evapotranspiration by phreatophytes and hydrophytes, relationship of pan evaporation, 415
Evapotranspiration, relation to environment and kind of plant, 524
Executive committee meeting, minutes, 135, 599

Fallout, radioactive, studies on the evaluation of gummed-paper collectors used in determinations, 857
Fallout, simple technique for determination, 391
Finnish granites, comparative radioactive ages, 398
Five-day mean temperatures, method for predicting, 397
Flat rivers, forecasting stages, 698
Flood flows, statistical treatment, 519
Flood frequency by regional synthesis, 419, 879
Floods, 267
Florida Gulf Coast, hydrography, 389
Fluvial sediment transportation, 897
Forecasting
decision, generalized analysis, 409
objective, Norfolk, Virginia area, 406
ocean waves, wave spectra and statistics, 264
stages on flat rivers, 698
use of prognostic charts, 385
weather analysis, motion and motion systems, 266
weather, synoptic-climatological aids, 400
Forecasts, five-day, numerical short-range prognoses, 390
Forecasts, numerical, sea-condition, 396
Forest overstory density, spherical densiometer for estimating, 270
Forest-cover, effects on snowpack, Central Sierra Snow Laboratory, 116
Fracture patterns in the Beartooth Mountains, Montana and Wyoming, 407
Fracture zone, Clipperton, northeastern equatorial Pacific, 400
Frequency analysis, log-normal nomogram, 33, 962
Frequency of floods by regional synthesis, 879
Frequency peak rates of runoff, 402
Frost protection airflow and heat transport patterns generated by wind machines, 254

GEK, accuracy, effects of cable design, 320
General, bibliography, 119, 271, 421, 588, 786, 971
General, papers, 450, 643, 831
General Secretary's report, 135, 599
Geochronology, Harwell analytical work, 543
Geochronology, symposium, 543
Geodesic line, 387
Geodesy
bibliography, 119, 271, 421, 588, 786, 972
discussion, 461, 579, 763
minutes, 439
papers 1, 8, 147, 156, 292, 297, 457, 651, 835, 841
Geodesy and the artificial satellite, 401
Geodetic leveling, reciprocal crossings, 404
Geodetic-type Worden gravimeters, observation accuracy, 147
Geoid, Columbus, 394, 841
Geology and ground-water hydrology of San Luis Obisbo County, California, 420
Geology, Huntington Lake area, Fresno County, California, 119
Geology, logic of, 412
Geomagnetic effect, solar, 389
Geomagnetic field components along radius of the Earth, 206, 414
Geomagnetic fluctuations at College, Alaska, 399
Geomagnetic horizontal field, equation for the oscillation of a magnet, 391
Geomagnetism program, IGY, 805
Geomorphology, watershed, quantitative analysis, 913
Geophysical Society of Hawaii, 145, 448
Georgia, southeastern, welded tuffs from a deep well, 404
Glaciation, multiple, since the ice age, 269
Glaciology status report, IGY, 627
Graf sea gravimeter, tests, 413
Granites and pegmatites, isotopic ages of zircon, 360
Granular media, flow through, 417
Gravimeters, observation accuracy of high-range Worden, 147
Gravimetrically computed deflections of vertical, 297
Gravitational strains in the Earth, 95
Gravity
and isostasy, central Quebec, 156
and magnetic fields, downward continuation of anomalies, 394
cross section of Coast Range of Venezuela, 372
data, calculations of thickness of crust, 392
determinations, improved pendulum apparatus, 409
drainage profiles, 395
measurements between Hazen and Austin, Nevada, 408
measurements in the northeastern Pacific Ocean, 835
measurements, thickness of Lemon Creek Glacier, Alaska, 745
meters, tidal, 8
observations at sea, 1, 292
status report, IGY, 623
waves, damping over permeable sea bed, 662
Ground surface, heat-transfer with air, 25
Ground vibration detector, magnification caused by partial resonance of its foundation, 928
Ground water
basins in Santa Barbara County, California, 421
circulation in deep wells, San Joaquin Valley, California, 417
flow, non-artesian, 511
hydrology and geology, San Luis Obisbo County, California, 420
in the Sacramento Valley, California, 416
recharge system, over perched water tables, 346
reservoirs, coastal, full utilization, 417
reservoirs, problems encountered in utilization, 417
resources of California, 415
uranium in, Texas and New Mexico, 386
Gulf Coast, Florida, hydrography, 389

Gulf of Mexico, micrometerological and oceanographic measurement program in conjunction with radio propagation tests, 411

Harwell, analytical work on geochronology, 543
Hearth hypothesis of the constitution of the Earth, 406
Heat flow at Grass Valley, California, 239
Heat-transfer coefficient between air and ground, 25
Heat transport and airflow patterns generated by wind machines, 254
High-altitude balloons, time-lapse motion-picture photography, 411
High-altitude soundings, use of constant-volume balloon, 395
Hiran measurements, statistical analysis, 763
Humidity-temperature soundings from aircraft, 404
Hurricanes, central pressure and maximum wind, maximum height of surge, 396
Hydrograph analysis and application, synthetic, use of storm and watershed characteristics, 418
Hydrologic data, criterion for length of record for moving arithmetic mean, 198
Hydrologic investigations at Hanford, Washington, 270, 724
Hydrologic studies, tracers, 402
Hydrology
  bibliography, 126, 267, 427, 592, 791, 977
  discussions, 114, 116, 260, 581, 765, 768, 773, 963
  minutes, 446
  papers, 68, 86, 198, 201, 209, 216, 219, 222, 233, 326, 333, 341, 346, 501, 511, 519, 524, 691, 698, 708, 718, 724, 730, 740, 745, 879, 885, 888, 897, 903, 908, 913, 921, 925
  reports, 108, 379
Hypothesis of formation of mountains and continents, 245

Iceland, Oceanographic island observatory, IGY, 1019
Igneous rocks, differentiation index as a tool for classifying, 410
Igneous rocks, radiation damage in zircon and its relation to ages of Paleozoic rocks in New England and adjacent Canada, 99
Infiltration rates, increase by utilizing organic residues, 326
Infiltrometer flow patterns, cylinder, influence of buffer ponds under moist soil conditions, 415
Infiltrometers, test of single-and double-ring types, 260
Instrumentation for the observation of the IGY satellites, 396
Internal friction in the mantle and rigidity of the Earth's core, 402
Internal stress, dependence upon irregularities in an elastic solid, 394
Internal waves, propogation and dissipation, 495
IGY
  bibliography, 784
  Bulletin 1, 611
  Bulletin 2, 627
  Bulletin 3, 799
  Bulletin 4, 815
  Bulletin 5, 991
  Bulletin 6, 1007
  Earth satellite program, 450
  salute, 449
  satellite tracking program, 412
  satellites, instrumentation for the observation, 396
  satellites, luminous intensities during the last flight stages, 400
International Participation, report of committee, 604
Ionosphere at Fort Churchill, Canada, ion composition, 397
Ionosphere-troposphere relationship, 387
Ionospheric physics program, IGY, 808
Isostasy and gravity in central Quebec, 156
Isotope dilution technique, radiogenic helium in zircon, 945
Isotope, lead, composition, mineralization pattern, and ore solutions, Missouri, 390
Isotope, oxygen, thermometer, 388
Isotopic ages of zircon from granites and pegmatites, 360, 409
Isotopic analyses, leads from Broken Hill, Australia, 557
Isotopic ratio, thorium^{232} to thorium^{230} in minerals, 404, 754

IUGG, Eleventh General Assembly, 145, 448, 449, 984
Jet stream and steady long waves, circulation in a dishpan experiment, 403

Labrador, observations on the growth of sea ice, 412
Lagrangian wind fluctuations from transosonde flights, 385
Lake Huron, age measurements on rocks, 412
Lake Superior region, A^{40}/K^{40} dating of rocks, 392
Lead isotope composition, mineralization pattern, and ore solutions, Missouri, 390
Leads and the continuous development of the crust, 399
Leads, anomalous from Ontario, 390
Leads, upper Great Lakes region, Ontario, 390, 552
Letters to the editor, 262, 778, 781, 782, 784, 960
Linear regressions, effect of nonrepresentative sampling of runoff, 333
Log-normal, frequency-analysis nomogram, 33, 962
Longitude and latitude status report, IGY, 623
Longitude determination, new timing method, 408
Love waves, generation, 397
Luminous intensities from IGY satellites during the last flight stages, 400
Lysimeter, floating, and its evaporation recorder, 765

Magnetic
  and gravity fields, downward continuation of anomalies, 394
  charts, mutually consistent, 400
  disturbance, solar geomagnetic effect, 389
  field to 163 km, rocket measurements at White Sands Proving Ground, 394
  intensity values, Taylor series as an interpolation formula, 781
  storms and atmospheric dynamo-action, sudden commencements, 401
  storms and aurorae, new model of, 175
  variation, solar daily, seasonal variability in E-region winds responsible, 411
Magnetism, remanent, Russell belt of gneisses, New York, 386

Magnetization, remanent, of Eocene formation from Oregon, 389
Magnetohydrodynamic theory of magnetic storms, 406
Mantle, polymorphism in the Earth, 569
Marine instruments and observations, recent developments, 406
Marine sediments, comparison of deep and shallow water, 401
'Mediterranean' and Pacific earthquake mechanisms, 349
Meeting
  AAAS in Indianapolis, 610
  Executive Committee, 135, 599
  Geophysical Society of Hawaii, 145, 448
  North Central Region, 145, 287,
  Pacific Northwest Region, 144, 287, 448, 610, 797
  Pacific Southwest Region, 287, 448, 610, 797, 989
  38th annual, 145
  39th annual, 448, 610, 797, 989
Meeting abstracts
  Pacific Northwest Region, 268
  Pacific Southwest Region, 414
  38th annual, 385
Melting temperatures of silicates, effect of volatile materials, 413
Members, directory, following page 288
Membership committee organization, 140
Membership Committee, status report, 608
Mesoanalysis of a tornado-producing situation in Texas, 407
Mesoanalysis of upper-air data, 390
Meteorites
  chondritic, existence of groups, 388
  thorium determination, 386
  uranium and barium contents, 393
  uranium-helium ages, 566
Meteorological
  analysis, 587
  instrumentation used during Project Prairie Grass, 410
  measurements from a minimum satellite, 469
  research by high-altitude manned balloons, 404
  variable, concentration of nuclear debris, 398
Meteorology
  air pollution, 398
  bibliography, 123, 274, 425, 590, 788, 974
  discussions, 254, 257, 960, 962
  minutes, 441
  papers, 17, 21, 25, 33, 38, 44, 166, 171, 308, 462, 469, 657, 857
  report, 954
  status report, IGY, 627
Micro-environmental gradients, field installation for automatic recording, 166
Micrometeorological and oceanographic measurement program in conjunction with radio propagation tests, 411
Micrometeorological measuring system, semi-automatic, 408
Micrometeorological program of Texas A and M in Nebraska, 393
Microscopic petrography, 119
Microseism amplitude at Corvallis, Oregon, correlation with components of atmospheric pressure gradient, 269
Microseisms, origin and propagation of 2- to 6- second, 354
Microseisms, two-second, Southern California, 393
Microstructure of the sea, thermal, new method for measuring, 410
Microvariations of water vapor in the lower troposphere, 400
Mineral ages, measurement, 385
Mineralization pattern, lead isotope composition, and ore solutions, Missouri, 390
Mineralography, petrographic, 118
Minerals, isotopic ratio of thorium^{232} to thorium^{230}, 404, 754
Minerals of California, 785
Minutes
  Executive Committee meeting, 135, 599
  General Assembly, 438
  Geodesy, 439
  Hydrology, 446
  Meteorology, 441
  Oceanography, 444
  Seismology, 440
  Tectonophysics, 447
  Terrestrial magnetism and electricity, 443
  Volcanology, Geochemistry, and Petrology, 445
Missouri, relationships between lead isotope composition, mineralization pattern, and ore solution composition, 390
Moisture movement in porous materials under temperature gradients, 222
Moisture movement, tracing in 'slick-spot' soils with radiosulfur, 397
Monazite, abundance and distribution of uranium and thorium, 939
Montana and Wyoming, fracture patterns in the Beartooth Mountains, 407
Montana, zircons of Archean rocks from the Beartooth Mountains, 393
Moonwatch observing methods, IGY, 1010
Mountains and continents, hypothesis of formation, 245

Natural water, Soviet methods of reporting and displaying chemical results, 219
Nebraska, life history of tornadoes, June 1955, 395
Nebraska, Texas A and M micrometeorological program, 393
Nepheline-kalsilite system, phase and structural relations, 407
Nevada, gravity measurements between Hazen and Austin, 408
New Britain, deflections of the vertical, 578
New Mexico
  full development of water resources, 419
  increase in area and density of salt cedar, 420
  rocket measurements at White Sands Proving Ground, 394
  uranium and radium in ground waters, 386
  zircons from Animas stock, 385
New York, radiotracer experiments in Mohawk River, 406
New York, remanent magnetism of the Russell belt of gneisses, 386
Nomogram, log-normal frequency analysis, 33, 962
Non-artesian ground-water flow, 511

Nonrepresentative sampling, effect on linear regressions as applied to runoff, 333
Non-tidal drift in estuaries, 403
North America
atlas of paleographic maps, 118
results obtained with Cambridge pendulum apparatus, 457
wind fields in lower stratosphere, 389
North Central Region, 145, 287, 448
Notes, 129, 279, 433, 594, 793, 979
Nuclear debris, concentration in the air, 398
Numerical prediction, 409
Numerical short-range prognoses in five-day circulation forecasts, 390

Occultations, surveying, 394
Ocean circulation, near-surface, from tritium measurements, 392
Ocean floor southeast of the Blake Plateau, seismic study, 395
Ocean waves in the band of 1 to 100 cycles per kilosecond, 400
Ocean waves, observing and forecasting by methods of wave spectra and statistics, 264, 778
Ocean waves, off-shore recording, 407
Oceanic and atmospheric carbon, radiocarbon evidence on dilution, 387, 643
Oceanographic
and micrometerological measure program in conjunction with radio propagation tests, 411
island observatory in Iceland, IGY 1019
observations of the Pacific, 785
profession recruitment problems, 386
Oceanography
bibliography, 124, 275, 426, 591, 789, 975
discussions, 584, 760
minutes, 444
papers, 50, 56, 62, 65, 191, 314, 320, 483, 495, 662, 667, 675, 681, 688, 864, 867
status report, IGY, 627
Oceans in the climates of the Pleistocene, 405
Off-shore recording of ocean waves, 407
Ohio, time-of-flow studies, Ottawa River, 407
Ontario, anomalous leads from the upper Great Lakes region, 390, 552
'Operation Wet-Blanket' gets under way, 414
Ore solutions, composition, lead isotope composition, and pattern of mineralization, Missouri, 390
Oregon, correlation of microseism amplitude at Corvallis with components of atmospheric pressure gradient, 269
Oregon, remanent magnetization of Eocene formation, 389
Organic residues, utilizing to increase infiltration rates, 326
Oscillation of air particles and effects on trajectory in the atmosphere, 397
Oxygen isotope thermometer, 388

Pacific
and 'Mediterranean' earthquake mechanisms, 349
Clipperton fracture zone, 400
Northwest regional meeting, 144, 268, 287, 448, 610, 797
Ocean, northeastern, gravity measurements, 835
oceanographic observations, 785
Southwest regional meeting, 287, 414, 448, 610, 797, 989
Paleographic maps, North America, 118
Pegmatites and granites, isotopic ages of zircon, 360
Pendulum apparatus for gravity determinations, improved, 409
Personalia, 132, 282, 436, 596, 795, 982
Petrographic mineralography, 118
Petrography, microscope, 119
Phase and structural relations in the nepheline-kalsilite system, 407
Phreatophyte areas, conservation of water by channelization and drainage, 420
Phreatophyte problem, 418
Phreatophytes, eradication and control, 416
Physical and statistical approaches to the problem of weather prediction, 402
Physiographic provinces, deep-sea, and crustal structure, 394
Plagioclase, δ_c spacing, 389
Pole shift, aperiodic, possibility, 397
Polymorphism, Earth's mantle, 569
Porous materials, moisture movement under temperature gradients, 222
Power-spectrum analysis of sonic anemometer wind and temperature measurements, 407
Prairie surface, temperature distribution, 391
Precipitation
gage intake tube, heated, 262
patterns, multiple-level radar maps, 398
precision of estimation of missing data, 657
processes as revealed by radar echoes, 387
type, mean temperature from 1000 to 500 mb as a predictor, 411
Pressure tendency and vertical velocity, a linear theory, 391
Prognoses, numerical short-range, incorporated in five-day circulation forecasts, 390
Prognostic charts in weather forecasting, 385
Project Prairie Grass, 386, 389, 403, 410
Pseudo-characteristics, 65
Pseudoleucite, origin, 391
Puget Sound, tidal currents and dispersal of fresh water, 268
Pyrheliometer, Eppley, characteristics, 38

Quarries, flooded, for oceanographic studies, 688
Quartz in water at high temperatures, solubility, 413

Radar and upper-air programs, Weather Bureau, recent developments, 395
Radar echoes reveal precipitation processes, 387
Radar maps, multiple-level, precipitation patterns, 398
Radiation damage in zircon and ages of Paleozoic igneous rocks, 99
Radiation during a total solar eclipse, 17
Radioactive
ages, from some Finnish granites, 398
fallout, evaluation of gummed-paper collectors, 857
liquid wastes, geological conditions at Hanford regulate ground disposal, 269
transfer in the Earth's mantle, 931

waste, disposal on land, 395
wastes, ion exchange and hydraulic phenomena in underground movement, 269
wastes, travel time in natural waters, 391
Radioactivity from rain, 405
Radiocarbon evidence on dilution of atmospheric and oceanic carbon, 387, 643
Radiogenic helium determination in zircon, 945
Radiosulfur, tracing moisture movement in 'slick-spot' soils, 397
Radiotracer experiments in Mohawk River, New York, 406
Rain, distribution of radioactivity, 405
Rain initiation, effect of air polution, 392
Rainfall
excessive, time-interval distribution, 408
frequency of point and areal mean rates, 960
intensity and topography in northern California, correlation, 398
kinetic energy, its relationship to erosion losses, 413
point, areal representativeness, 341
runoff relation for small basins, 216
Rayleigh waves, crustal structure from phase velocity, 402
Recruitment problems in oceanographic profession, 386
Refraction measurements, seismic, in the eastern Caribbean, 390
Remanent magnetism of the Russell belt of gneisses, New York, 386
Remanent magnetization of Eocene formation from Oregon, 389
Reprinting out-of-print *Transactions*, 447
Research rocket program, IGY, 815
Resistivity curves, potentials about a point electrode for a two-, three-, and four-layer Earth, 117
Reviews and abstracts, 117, 118, 119, 264, 266, 267, 268, 385–421, 587, 785, 971
Rill and sheet erosion, affecting factors, 889
Rocket measurements at White Sands Proving Ground, New Mexico, 394
Rocket program, IGY, 812
Rockets and satellites, radio tracking system, IGY, 633
Rockoon firings in the Arctic, IGY, 998
Rocks, anistrophy under simple compression, 89
Rotating axial symmetrical solid body, stability of the motion in a fluid, 831
Rotation of the Earth, 401
Runoff
Committee report, 379
effect of nonrepresentative sampling on linear regressions, 333
investigation to evaluate a precipitation-increasing program, 418
near the Columbia River estuary, effect of logging, 270
relations between low and high frequency peak rates, 402
relation for small basins, 216
Russian scientific literature, translation, 447, 448

Salt cedar in New Mexico, increase in area and density, 420
Salt cedar (*Tamarix gallica*), results pertaining to control, 414
Salt-water intrusion pertaining especially to Lake Washington, 270
Sand transport by wind, 171
Satellite
and geodesy, 401
data, correcting for unavoidable smoothing, 395
IGY, luminous intensities during the last flight stages, 400
meteorological measurements, 469
program, IGY, 450
reports, USSR, IGY, 991
scientific uses, 401
tracking program, IGY, upper atmosphere data expected, 412
Scientific uses of Earth satellites, 401
Sea
bed, damping of gravity waves, 662
condition forecasts, numerical, 396
gravity observations, 1, 292
ice at Hopdale, Labrador, observations on the growth, 412
level, axial slope in Chesapeake Bay, 62
vengeful, 268
water data, daily classification, 191
wave recorder, electronic, 50
Sediment
fluvial transportation, 897
importance of channel erosion as a source, 908
importance of sheet erosion as a source, 903
laden streams, resistance, 420
load, modified Einstein procedure, 768
needed research, 925
symposium, 885
unmeasured discharge, relationship to mean velocity, 708
yield, relating to watershed variables, 921
yields, problems of predicting yields from watersheds, 885
Seismic
calculations of thickness of crust, 392
refraction measurements in the eastern Carribbean, 390
study of the ocean floor southeast of the Blake Plateau, 395
waves, shadow zones, travel times, and energies in the presence of an asthenosphere low-velocity layer, 529
Seismological Laboratory, CIT, progress report, 248
Seismology,
bibliography, 277, 428, 593, 792, 977
minutes, 440
papers, 89, 349, 354, 529, 750, 928
report, 248
status report, IGY, 623
Semi-arid countries, water supply and drainage, 501
Shear stresses and air velocity profiles on a mechanical wave boundary, 681
Sheet and rill erosion, affecting factors, 889
Sheet erosion, importance as a source of sediment, 903
Shoaling oscillatory waves, application of solitary wave theory, 56
Shoaling waves, properties, 760
Short-fetch wave-slope probability distributions, 405

Silicates, effect of volatile materials on the melting temperatures, 413
Sky temperatures in Imperial Valley, California, 308
Slick-spot soils, tracing moisture movement with radiosulfur, 397
Smoothing of artificial satellite data, 395
Snow, determining practical course consistencies, 270
Snow, report of the Committee, 108, 114
Snowmelt runoff, effect of hydroclimatic factors, 773
Snowpack, forest-cover effects, Central Sierra Snow Laboratory, 116
Soil overlying an impervious substratum, underdrainage into ditches, 730
Soil temperature, annual range, 718
Soils, probe for measurement of thermal conductivity, 691
Solar activity program, IGY, 800
Solar eclipse, radiation, 17
South Pole winter weather review, IGY, 996
Spectra of wind waves, 864
Spectrometers, rocket-borne, ion composition of the ionosphere at Fort Churchill, Canada, 397
Sphene, abundance and distribution of uranium and thorium, 939
Spreading water for recharge, alleviating surface clogging, 419
Squall lines and thunderstorms, after-effects, 410
Statutes and By-Laws, report of committee, 608
Stereoseismic exploration, 415
Storms, correlation of characteristics, 233
Storms, intensity and frequency in Gulf of Alaska, 44
Storm-water flow, 387
Strains in the Earth, self-gravitational, 95, 970
Stratosphere, lower, wind fields over North America, 389
Stratospheric temperatures, diurnal variations in Arctic, 462
Stream, lengths, determination from topographic maps, 86
Streamflow into a tidal estuary, 581
Strontium content of deep-sea cores, variations, 410
Submarine ridges, Arctic Ocean, IGY, 1016
Submerged vertical structures, photography, 314
Subsidence in the Santa Clara Valley, California, 418
Substratum, impervious, underdrainage into ditches in overlying soil, 730
Suggestions to authors, 284
Sunspot, current numbers, IGY, 815
Supergene alteration of zinc-lead deposits, 408
Suppressing evaporation from water surfaces, 403, 740
Surface strain, dependence upon irregularities in an elastic solid, 394
Surveying by occultations, 394
Symposium on watershed erosion and sediment yields, 885
Synoptic-climatological aids to weather forecasting, 400
Synthesis of zoisite in the pressure range 1000–5000 bars, 403

Tamarisk and eucalyptus, time course studies of transpiration, 416
Tamarisks, spread in the Pacific Southwest, influence upon the indigenous vegetation, 415
Taylor series as an interpolation formula with magnetic intensity values, 781
Tectonophysics
  bibliography, 128, 278, 433, 793, 978
  discussions, 970
  minutes, 447
  papers, 95, 245, 372, 569
Temperature distribution just above the prairie surface, 391
Temperature from 1000 to 500 mb as a predictor of precipitation type, 411
Temperatures, five-day mean, method for predicting, 397
Terrestrial Magnetism and Electricity
  bibliography, 121, 272, 423, 589, 786, 973
  minutes, 443
  papers, 175, 306, 849
Texas A and M, micrometeorological program in Nebraska, 393
Texas, uranium and radium in ground waters, 386
Thermal conductivity, probe for measurement in frozen soils in place, 691
Thermal microstructure of the sea, new method for measuring, 410
Thickness, investigation of 1000-500 mb changes, 393
Thirty-eighth annual meeting, 145, 385, 438
Thirty-ninth annual meeting, 448, 610, 797, 989
Thorium and uranium in granitic rocks, 939
Thorium in meteorites, 386
Thorium^{232}, method to determine the isotopic ratio to thorium^{230} in minerals, 404, 754
Thunder storm occurence, large scale vertical motion, July 1955, 390
Thunderstorms and squall lines, after-effects, 410
Tidal current, rotary, wind influence, 867
Tidal currents and dispersal of fresh water in Puget sound and environs, 268
Tidal estuary, estimating streamflow into, 581
Tidal gravity meters, 8
Tide and tidal current, offshore distribution, 675
Time-lapse cameras at high altitude for observing weather dynamics, 404
Time-of-flow studies, Ottawa River, Lima, Ohio, 407
Topographic maps, determination of stream lengths, 86
Topography and rainfall intensity in northern California, correlation, 398
Tornado-producing situation in Texas, mesoanalysis, 407
Tornadoes, Scottsbluff, Nebraska, life history, June 1955, 395
Tornadoes spread disease, 399
Tracers, radioactive, in hydrologic studies, 402
Transactions, reprinting, 447
Transosonde flights, Lagrangian wind fluctuations, 385
Travel time of radioactive wastes in natural waters, 391
Tritium measurements, near-surface ocean circulation, 392
Troposphere-ionosphere relationship, 387
Troposphere, lower, microvariations of water vapor, 400
Tropical storm relationships, 405
Turbulence by horizontal windshear, 402

Two-dimensional gravity drainage profiles, 395

Underdrainage into ditches in soil overlying an impervious substratum, 730
Ungaged catchments, frequency of discharges, 963
Upper-air and radar programs, Weather Bureau, recent developments, 395
Upper-air data, experiment in mesoanalysis, 390
Upper atmosphere, committee report, 954
Upper atmosphere program status report, IGY, 799
Uranium and barium contents of meteorites, 393
Uranium and radium on ground water, Texas and New Mexico, 386
Uranium and thorium in zircon, sphene, apatite, epidote, and monazite in granitic rocks, abundance and distribution, 939
Uranium-helium ages, iron meteorites, 566
USSR satellite reports, preliminary summary, IGY, 991

Velocity, relationship to unmeasured sediment discharge, 708
Velocity, vertical, and pressure tendency, a linear theory, 391
Venezuela, gravity cross sections of Coast Range, 372
Vertical motion, large scale, and thunderstorm occurrence in July 1955, 390
Vertical velocity and weather, 405
Vibration detector, ground, magnification caused by partial resonance of its foundation, 928
Virginia earthquake of August 27, 1833, 398
Virginia, Norfolk, objective forecasting, 406
Viscosities, eddy, in open channels, 406
Volcanic eruption in Belgian Congo, 960
Volcanism of probable early paleozoic in the Georgia-Florida region, 404
Volcanology, Geochemistry, and Petrology
  bibliography, 127, 277, 430, 593, 793, 978
  minutes, 445
  papers, 99, 239, 360, 539, 543, 547, 552, 557, 564, 566, 754, 931, 939, 945

Washington, geological conditions at Hanford regulate ground disposal of radioactive liquid wastes, 269
Washington, hydrologic investigations at Hanford, 270, 724
Water levels of coastal New England, effect of winds 400
Water
  minimum yield from small agricultural watersheds, 201
  movement, change in relationship with wind at higher wind speeds, 584
  resources development by conjunctive operation of surface and ground-water reservoirs, 416
  resources in New Mexico and Arizona, full development, 419
  spreading, utilizing organic residues to increase infiltration rates, 326
  supply and drainage in semi-arid countries, 501
  surfaces, evaporation suppression, 740
  tables, perched, under artificial recharge, 346
  vapor in the lower troposphere, microvariations, 400
  yield improvement in Arizona, 413
Watershed
  geomorphology, quantitative analysis, 913
  small agricultural, minimum water yield, 201
  small forested, calibration, 403
  variables, relating to sediment yield, 921
Wave
  boundary, direct shear stresses and air velocity profiles, 681
  derivatives, method, 483
  heights and lengths, joint distribution, 387
  measurements along the California coast, 667
  slope, probability distributions, 405
  solitary, application to shoaling oscillatory waves, 56
  spectra for observing and forecasting ocean waves, 778
Waves, internal, propagation and dissipation, 495
Waves, shoaling, properties, 760
Weather
  analysis and forecasting, motion and motion systems, 266
  and vertical velocity, 405
  dynamics, use of time-lapse cameras, 404
  forecasting, certain synoptic-climatological aids, 400
  prediction, physical and statistical approaches to the problem, 402
Weather Bureau
  general circulation research program, 406
  surface observational program, recent developments, 413
  upper-air and radar programs, recent developments, 395
Welded tuffs from a deep well in southeastern Georgia, 404
Whistlers and related phenomena, IGY, 1012
Wind
  above 100,000 feet, measurement of rocket-ejected chaff and metalized parachutes, 399
  effect on coastal water levels of New England, 400
  fields in lower stratosphere over North America, 389
  generated sea, directional spectrum, 399, 402
  influence on a rotary tidal current, 867
  machines, mean airflow and heat transport patterns, 254
  maximum, and central pressure of hurricanes maximum height of surge, 396
  profile, diabetic, 21
  shear, horizontal, formation of turbulence, 402
  speeds, relationship with surface-water movement, 584
  structure, diurnal variations, 387
  transport of sand, 171
  waves, spectra, 864
Winter weather review of South Pole, IGY, 996
World day program for the IGY, 1000
World days during the IGY, 631
Wyoming, zircons of Archean rocks from the Beartooth Mountains, 393

Zinc-lead deposits, supergene alteration, 408

Zircon
abundance and distribution of uranium and thorium in, 939
Animas stock, New Mexico, 385
Archean rocks from the Beartooth Mountains, Montana and Wyoming, 393
Bald Rock Batholith, California, 398
determination of radiogenic helium in it by stable isotope dilution technique, 945
isotopic ages, granites and pegmatites, 360, 409
pegmatite, alpha-helium ages, 390
radiation damage and its relation to ages of Paleozoic igneous rocks in New England and adjacent Canada, 99

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Gravity Observations at Sea in USS *Conger*, Cruise III*

G. Lynn Shurbet and J. Lamar Worzel

Abstract—Principal facts, including free-air and simple Bouguer anomalies, are presented for 60 gravity observations at sea. A Vening Meinesz pendulum apparatus was used during the gravity measuring cruise of USS *Conger* (SS477), Cruise III.

Excluding anomalies associated with the Puerto Rico Trench and the continental margin, free-air anomalies observed on a line between San Juan, P. R., and New London, Conn., are −10 to −50 mgal. If the standard oceanic crustal section of Worzel and Shurbet is adopted as a reference, these anomalies can be explained by variations of the sediment or, the crustal rock thicknesses of not more than 1 km from normal oceanic thicknesses, or both.

Introduction—Gravity observations at 60 positions (Fig. 1) were made in 1954 during gravity Cruise III of USS *Conger* (SS 477). Three profiles of closely spaced (5 to 10 mi) observations were made, two in the Bahama Islands and one between St. Thomas and St. Croix, V. I. Observations were made at about 50 mi intervals between San Juan, P. R., and New London, Conn. The principal facts for these observations, including free-air and simple Bouguer anomalies, are presented in this paper. Isostatic corrections are being computed by the Mapping and Charting Research Laboratory, Ohio State University under the direction of W. A. Heiskanen.

General—A pendulum apparatus developed by *Vening Meinesz* [1929] for use at sea in a submerged submarine was used to make these observations. *Worzel* and *Ewing* [1950, 1952] and *Worzel, Shurbet,* and *Ewing* [1955ab] have described modifications of the basic apparatus and associated equipment to improve techniques of observation and data reduction. A long-period pendulum apparatus designed by *Vening Meinesz* [1941] was used to observe the horizontal accelerations [*Browne*, 1937].

The observation program of *Vening Meinesz* [1929] was modified by the incorporation of the crystal chronometer, the use of a single speed for the recording paper, and the use of the long-period pendulum apparatus.

Periods read from the photographic records were corrected for temperature, air density, isochronism, chronometer rate, tilt of the swinging plane, and amplitude to give values of observed gravity at the depth of submergence. These values were corrected to the sea surface, for the second order effects of acceleration [*Browne*, 1937], and for the Eötvös effect to give values of observed gravity at the sea surface. Each value is the average value of observed gravity over a horizontal distance of about 1 mile, since each observation requires about 30 minutes while the submarine is traveling at about two knots. The International Formula of Gravity of 1930 was used to compute the free-air anomalies, and densities of 2.84 for the crustal rocks and 1.04 for sea water were used to compute the simple Bouguer anomalies.

Ewing, Worzel, and *Shurbet* [1956] have estimated the uncertainty of free-air anomalies determined by typical observations such as those made during this cruise to be ± 3.6 mgal.

Primary base station—The Lamont Geological Observatory Base 1 (Serial 1501) is the primary base for these observations. *Shurbet* and *Worzel* [in press, a] have adopted

$$g = 980.2584 \text{ cm/sec}^2$$

for the LGO Base, relative to the U. S. Coast and Geodetic Survey base in the Department of Commerce Building, Washington, D. C. [980.118 cm/sec², *Duerksen*, 1949].

Pendulum standardization—Observations were made at the LGO Base before and after this cruise to determine the base periods for pendulums 4, 5, and 6. Periods determined by individual observations are shown in Table 1. The agreement between observations before and after the cruise is

* Contribution No. 220, Lamont Geological Observatory of Columbia University.

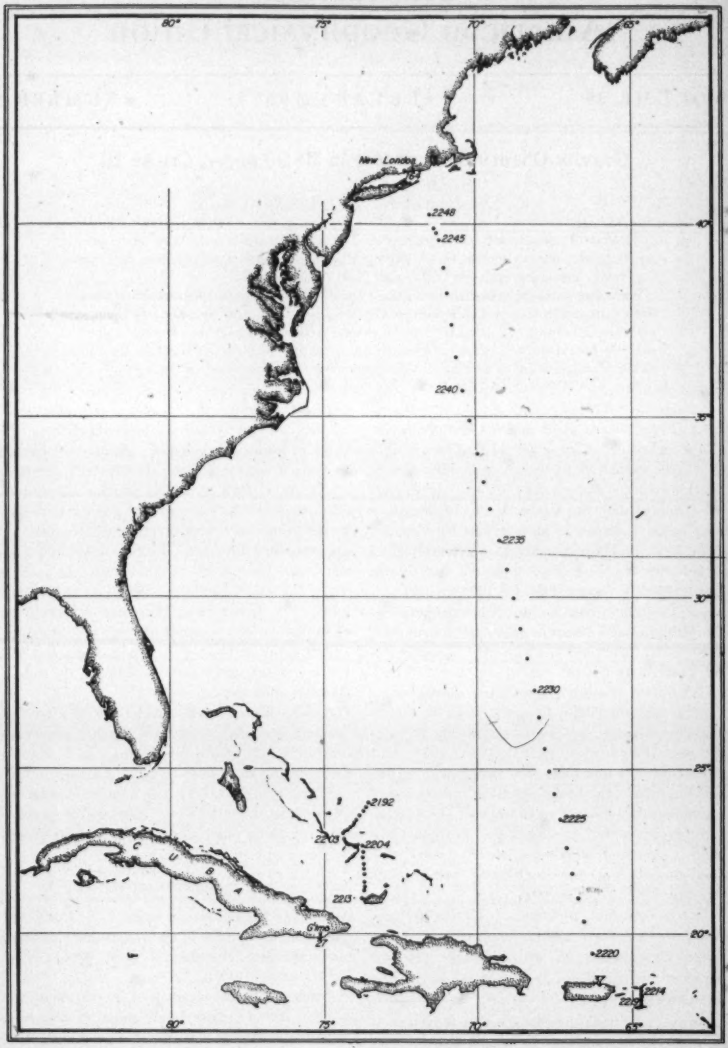

FIG. 1 – Station locations USS *Conger* (SS 477), Cruise III, January–March 1954, serial numbers are indicated

TABLE 1 – *Pendulum standardization USS Conger, Cruise III, Lamont Geological Observatory Base 1, 41°00'.3N, 73°54'.5W, g = 980.2584 cm/sec²*

Observation	Date	Pendulum 4	Pendulum 5	Pendulum 6
Before *Conger*, Cruise III				
BUG 29-1	Dec. 29, 1953	1.0055955	1.0055983	...
BUG 29-2	Dec. 30, 1953	1.0055955	1.0055975	...
BUG 29-3	Dec. 31, 1953	...	...	1.0055972
BUG 29-4	Dec. 31, 1953	1.0055969	1.0055979	...
BUG 29-5	Dec. 31, 1953	1.0055963	1.0055986	...
BUG 29-6	Jan. 5, 1954	...	...	1.0055973
Mean		1.0055961	1.0055981	1.0055973
After *Conger*, Cruise III				
CGIII 62-1	Apr. 6, 1954	1.0055953	1.0055974	...
CGIII 62-2	Apr. 7, 1954	1.0055949	1.0055966	...
CGIII 62-3	Apr. 7, 1954	1.0055950	1.0055971	...
CGIII 62-4	Apr. 7, 1954	1.0055956	1.0055970	...
CGIII 62-5	Apr. 9, 1954	1.0055950	1.0055968	...
CGIII 62-6	Apr. 9, 1954	...	...	1.0055961
CGIII 62-7	Apr. 9, 1954	1.0055954	1.0055969	...
CGIII 62-8	Apr. 13, 1954	...	...	1.0055971
Mean		1.0055952	1.0055970	1.0055966
Adopted value		1.0055955	1.0055974	1.0055969

TABLE 2 – *Gravity observations at secondary bases, Conger, Cruise III*

Observation	Date	Pendulum 4	Pendulum 5	Pendulums 4 & 5
New London, Conn., 41°23.5'N, 72°05.5'W				
CGIII 1-1	Jan. 20, 1954	980.2932	980.2940	980.2936
CGIII 1-2	Jan. 20, 1954	980.2928	980.2944	980.2936
CGIII 1-3	Jan. 20, 1954	980.2959	980.2947	980.2953
Serial 164(f)		Adopted value		980.294
New London, Conn., 41°23.6'N, 72°05.6'W				
CGIII 1-6	Jan. 25, 1954	980.2949	980.2936	980.2943
Serial 164(c)		Adopted value		980.294
Guantanamo Bay, Cuba, 19°54.5'N, 75°08.9'W				
CGIII 24-1	Jan. 31, 1954	978.7459	978.7481	978.7470
CGIII 24-2	Jan. 31, 1954	978.7452	978.7490	978.7471
CGIII 24-4	Jan. 31, 1954	978.7477	978.7494	978.7486
CGIII 24-6	Jan. 31, 1954	978.7455	978.7494	978.7475
Serial 27(a)		Adopted value		978.748
San Juan, P. R., 18°26.9'N, 66°05.5'W				
CGIII 31-1	Feb. 27, 1954	978.6835	978.6835	978.6835
Serial 37(c)		Adopted value		978.684
New London, Conn., 41°23.5'N, 72°05.5'W				
CGIII 61-1	Mar. 4, 1954	980.2961	980.2942	980.2952
CGIII 61-3	Mar. 5, 1954	980.2953	980.2955	980.2954
CGIII 61-5	Mar. 5, 1954	980.2944	980.2940	980.2942
Serial 164(g)		Adopted value		980.295

TABLE 3 – *Comparison of gravity values at secondary bases, Conger Cruise III*

Observation	Date	Latitude	Longitude	Elevation	Gravity
New London, Conn.		° ′	° ′	*m*	*cm/sec²*
Conger, cruise III..	1954	41 23.5N	72 05.5W	0	980.294
Conger, cruise III..	1954	41 23.6N	72 05.6W	0	980.294
Conger, cruise III..	1954	41 23.5N	72 05.5W	0	980.295
Diablo[a]	1953	41 23.6N	72 05.6W	0	980.296
Diablo[a]	1953	41 23.5N	72 05.5W	0	980.297
Argonaut[b]	1948	41 23.6N	72 05.5W	0	980.295
Argonaut[b]	1948	41 23.5N	72 05.5W	0	980.298
Tusk[b]	1947	41 23.6N	72 05.5W	0	980.294
Frost gravimeter[a]	1948	41 23.6N	72 05.5W	3	980.2948
Frost gravimeter[a]	1948	41 23.5N	72 05.5W	3	980.2940
Guantanamo Bay, Cuba					
Conger, cruise III..	1954	19 54.5N	75 08.9W	0	978.748
S-21[b]	1928	19 54.5N	75 08.9W	0	978.748
S-48[c]	1932	19 54.5N	75 08.9W	0	978.745
Frost gravimeter[d]	1954	19 54.5N	75 08.9W	1.5	978.7528
San Juan, P. R.					
Conger, cruise III..	1954	18 26.9N	66 05.5W	0	978.684
Diablo[a]	1953	18 27.9N	66 06.7W	0	978.680
Diablo[a]	1953	18 27.7N	66 05.5W	0	978.685
S-21[b]	1928	18 27.8N	66 06.8W	0	978.695
Frost gravimeter[f]	1953	18 27.9N	66 06.7W	2	978.6816

[a] *Ewing, Worzel,* and *Shurbet* [in press].
[b] *Vening Meinesz* and *Wright* [1930].
[c] *Collins* [1933].
[d] *Shurbet* and *Worzel* [in press, b].
[e] *Shurbet* and *Worzel* [in press, a].
[f] *Shurbet* and *Ewing* [1956].

satisfactory, and the over-all mean for each pendulum has been adopted as its base period.

Constants used for data reduction—Temperature and density coefficients [*Ewing, Worzel,* and *Shurbet,* in press] and periods at the LGO Base listed below are pendulum constants adopted for this cruise.

Temperature coefficients (determined in 1947): $C_4 = 98.4 \times 10^{-7}$ sec/°C; $C_5 = 99.0 \times 10^{-7}$ sec/°C; $C_6 = 98.0 \times 10^{-7}$ sec/°C.

Density coefficients (determined in 1948): $D_4 = 1319 \times 10^{-7}$ sec/unit relative air density; $D_5 = 1346 \times 10^{-7}$ sec/unit relative air density; $D_6 = 1337 \times 10^{-7}$ sec/unit relative air density.

Base station pendulum periods: $T_4 = 1.0055955$ sec; $T_5 = 1.0055974$ sec; $T_6 = 1.0055969$ sec, at 30°C, LGO Base, $g = 980.2584$ cm/sec².

Secondary base observations—Secondary base observations were made at New London, Conn., Guantanamo Bay, Cuba, and San Juan, P. R. (Table 2). The agreement between observations at each location is satisfactory. In Table 3, these values of observed gravity are compared with pre-

TABLE 4– *Gravity observations, USS Conger, Cruise III, January–March 1954; Observer, Hugh Traphagen; based on the LGO Base (980.2584 cm/sec²)*

Serial no. (1)	Station no. (2)	Date (3)	Latitude North (4)	Longitude West (5)	Sounding (6)	Observed gravity (7)	Internation. formula gravity (8)	Free air anomaly (9)	Bouguer anom. (10)
		1954	° ′	° ′	m	cm/sec²	cm/sec²	mgal	mgal
164(f)	1	Jan. 20	41 23.5	72 05.5	6	980.294	980.305	−11	−10
164(c)	1	Jan. 25	41 23.6	72 05.6	6	.294	.305	−11	−10
2192	2	Jan. 28	23 58	73 32	5342	978.861	978.899	−38	365
2193	3	Jan. 28	23 51	73 37	5279	.844	.892	−48	350
2194	4	Jan. 28	23 44	73 42	5046	.834	.884	−50	331
2195	5	Jan. 28	23 36	73 49	4827	978.811	978.875	−64	300
2196	6	Jan. 28	23 27	73 55	4657	.785	.865	−80	271
2197	7	Jan. 28	23 22	73 59	4515	.770	.860	−90	250
2198	8	Jan. 28	23 19	74 02	4688	.765	.856	−91	263
2199	9	Jan. 28	23 15	74 08	4513	.771	.852	−81	259
2200	10	Jan. 28	23 11	74 13	4109	978.773	978.848	−75	235
2201	11	Jan. 28	23 08	74 18	2658	.799	.844	−45	155
2202	12	Jan. 29	23 04	74 22	2716	.790	.840	−50	155
2203	13	Jan. 29	22 54	74 20	1673	.836	.829	7	133
2204	14	Jan. 29	22 41	73 44	1003	.873	.815	58	134
2205	15	Jan. 29	22 30	73 43	1035	978.839	978.804	35	113
2206	16	Jan. 29	22 21	73 43	1832	.782	.794	−12	126
2207	17	Jan. 29	22 09	73 41	2021	.764	.782	−18	134
2208	18	Jan. 29	22 00	73 41	1647	.770	.772	−2	122
2209	19	Jan. 29	21 50	73 40	1505	.779	.762	17	131
2210	20	Jan. 29	21 36	73 40	1689	978.727	978.747	−20	107
2211	21	Jan. 29	21 28	73 39	2433	.658	.739	−81	102
2212	22	Jan. 29	21 21	73 41	2381	.647	.732	−85	95
2213	23	Jan. 30	21 06	73 45	2183	.652	.717	−65	100
27(a)	24	Jan. 31	19 54.5	75 08.9	10	.748	.646	102	103
2214	25	Feb. 18	18 14	64 44	53	978.674	978.553	121	125
2215	26	Feb. 18	18 08	64 44	1382	.568	.548	20	124
2216	27	Feb. 18	17 50	64 44	2156	.533	.532	1	164
2217	28	Feb. 18	17 56	64 44	3902	.426	.537	−111	183
2218	29	Feb. 18	18 00	64 44	3519	.422	.541	−119	146
2219	30	Feb. 19	18 03	64 42	3622	978.433	978.544	−111	162
37(c)	31	Feb. 27	18 26.9	66 05.5	9	.684	.565	119	120
2220	32	Feb. 27	19 22.5	66 20.0	6875	.250	.616	−366	152
2221	33	Feb. 27	20 22.5	66 34.0	5394	.660	.674	−14	393
2222	34	Feb. 27	21 06.5	66 45.0	5540	.731	.717	14	432
2223	35	Feb. 28	21 51.5	66 55.5	5249	978.753	978.763	−10	386
2224	36	Feb. 28	22 37.5	67 06.5	5578	.778	.812	−34	387
2225	37	Feb. 28	23 28.0	67 19.0	5670	.821	.866	−45	383
2226	38	Feb. 28	24 15.0	67 30.0	5654	.867	.918	−51	375
2227	39	Feb. 28	24 55.5	67 40.5	5372	.945	.964	−19	386
2228	40	Feb. 28	25 36.5	67 50.0	5541	978.977	979.012	−35	383
2229	41	Mar. 1	26 32.0	68 01.5	5252	979.066	.078	−12	384
2230	42	Mar. 1	27 18.0	68 11.5	5036	.107	.133	−26	354
2231	43	Mar. 1	28 14.5	68 25.0	5041	.185	.203	−18	362
2232	44	Mar. 1	29 06.0	68 38.5	5082	.238	.268	−30	353
2233	45	Mar. 1	29 58.0	68 52.0	5152	979.282	979.335	−53	336
2234	46	Mar. 1	30 46.0	69 05.0	5268	.360	.398	−38	359
2235	47	Mar. 2	31 36.0	69 18.0	5216	.422	.465	−43	350
2236	48	Mar. 2	32 28.0	69 33.0	5217	.501	.535	−34	359
2237	49	Mar. 2	33 13.5	69 45.5	5370	.565	.597	−32	373

TABLE 4 – *Concluded*

Serial no. (1)	Station no. (2)	Date (3)	Latitude North (4)	Longitude West (5)	Sounding (6)	Observed gravity (7)	Internation. formula gravity (8)	Free air anomaly (9)	Bouguer anom. (10)
		1954	° ′	° ′	m	cm/sec²	cm/sec²	mgal	mgal
2238	50	Mar. 2	34 01.0	69 57.5	5278	979.633	979.663	−30	368
2239	51	Mar. 2	34 52.5	70 10.5	4852	.705	.735	−30	336
2240	52	Mar. 3	35 41.0	70 23.0	4335	.794	.804	−10	317
2241	53	Mar. 3	36 33.0	70 36.0	4229	.850	.878	−28	291
2242	54	Mar. 3	37 25.0	70 45.5	4021	.916	.953	−37	266
2243	55	Mar. 3	38 14.5	70 54.0	3437	979.986	980.025	−39	220
2244	56	Mar. 3	38 54.0	71 00.5	2839	980.049	.083	−34	180
2245	57	Mar. 3	39 36.0	71 11.5	2242	.092	.145	−53	116
2246	58	Mar. 3	39 46.5	71 16.5	1133	.160	.161	−1	84
2247	59	Mar. 3	39 53.5	71 20.5	446	.200	.171	29	63
2248	60	Mar. 4	40 14.5	71 31.5	83	980.203	980.202	1	7
164(g)	61	Mar. 4	41 23.5	72 05.5	6	.295	.305	−10	−9
1501	62	Apr. 6	41 00.25	73 54.45	−104	.2584	.270	−12	−24

vious values referenced in the table. It should be emphasized that observations at port stations are sometimes very difficult to make with the pendulum apparatus. Serious accelerations are introduced as the submarine bounces against the pier or swings and surges on the anchor chain, decreasing the accuracy of the results. Considering this reduced accuracy, all values at New London are in reasonable agreement. At Guantanamo Bay, the value from this cruise is identical with that from the S-21 [*Vening Meinesz* and *Wright*, 1930] and in good agreement with that from the S-48 [*Collins*, 1933]. The agreement of the gravimeter value [*Shurbet* and *Worzel*, in press, b] with the *Conger* and S-21 values is barely within the accuracy of the observations. No explanation is offered for the lack of agreement between the gravimeter and the S-48 values. At San Juan, the *Conger* value is in reasonable agreement with all other values except that from the S-21 which is believed to be too high by about 15 mgal [*Shurbet* and *Ewing*, 1956, p. 514].

Principal facts for the gravity observations—Table 4 shows the principal facts for these observations. Pertinent added information on column headings is: (2) the observation number assigned during the cruise; (4) the latitude of the mid-point of the observation; (5) the longitude of the mid-point of the observation; (6) the water depth in meters corrected according to the tables of *Matthews* [1939]; (8) the value of theoretical gravity in cm/sec² by the International Formula of Gravity of 1930, $\gamma_0 = 978.0490\ (1 + 0.0052884 \sin^2\phi - 0.0000059 \sin^2 2\phi)$; and (10) the simple Bouguer anomaly in milligals, assuming densities of 2.84 for the crustal rocks and 1.04 for sea water.

Free-air gravity anomalies—Since there are many additional gravity observations in the Bahama Islands, a discussion of the gravity anomalies for stations 2192 through 2213 of this cruise will be postponed. An interpretation of gravity anomalies throughout the Bahama Islands is now in progress at this laboratory.

The gravity anomalies for stations 2214 through 2219 in the Virgin Islands area have been discussed by *Shurbet*, *Worzel*, and *Ewing*, [in press] with additional gravity data in the area. A structure across the Virgin Bank and St. Croix was deduced, using seismic sections in the area as a guide. The gravity computations show the M-discontinuity to be about 29 km below sea level under the Virgin Bank and St. Croix, and about 22 km under the Anegada Trough. It was concluded that the crustal rock section under the Anegada Trough has been thinned by extension.

In Figure 2 a profile of the free-air gravity anomalies determined for stations between San Juan and New London is shown with a profile of the soundings made at each station. The large gravity anomalies at San Juan, in the Puerto Rico Trench vicinity, and at the 1000-fathom curve south of New London are the most obvious features on this profile. These features are already known in considerable detail [*Worzel* and *Ewing*, 1954; *Shurbet* and *Ewing*, 1956; *Worzel* and *Shurbet*, 1955b], and no further discussion is possible from these new data.

The gravity anomalies between the Puerto Rico Trench and the 1000-fathom curve south of New London are about −10 to −50 mgal. Variations in sediment and crustal rock thicknesses and, of

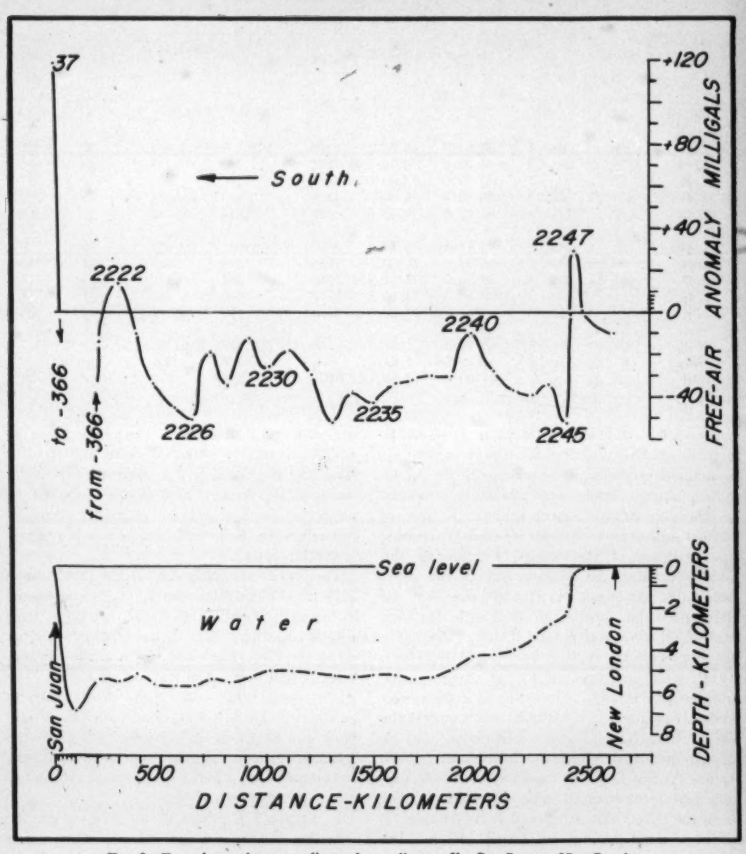

FIG. 2 – Free-air gravity anomalies and sounding profile, San Juan to New London

course, density can explain these anomalies. If the standard oceanic crustal section (5 km of water of density 1.03, 1 km of sediments of density 2.30, and 4.5 km of crustal rocks of density 2.84 overlying the mantle of density 3.27) of *Worzel* and *Shurbet* [1955a] is accepted as a basis of computation, then a thickening or thinning, depending on the water depth, of the sediments or the crustal rocks by less than one kilometer is necessary to satisfy most of the observed gravity anomalies. To satisfy the anomalies over the continental rise, both the sedimentary and crustal rock sections are probably thicker than standard by about one kilometer [*Worzel* and *Shurbet*, 1955b].

Acknowledgments—This cruise was possible through the assistance and cooperation of the Commander Submarine Force, Atlantic Fleet, and the officers and men of USS *Conger*, Lt. Cdr. W. E. Cummins commanding. Part of the equipment used was loaned by the Woods Hole Oceanographic Institution and the Naval Ordnance Laboratory. H. Traphagen made the observations, E. Skinner assisted in the computations, and A. Trefzer made the drawings. This work was carried

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Improvements in Tidal Gravity Meters and Their Simultaneous Comparison

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Abstract—The measurements obtained in instruments such as tidal gravity meters have led to the development of a photoelectric optical system that is not subject to the forms of drift associated with most reading systems of this type. In addition a much improved servo-system with a compensating network has been employed in these measurements and will be described. The results of measurements made at Austin, Texas with two tidal gravity meters recording simultaneously are given. They indicate an accuracy of better than 1 microgal.

Introduction—The previously described tidal gravity meter [*Clarkson* and *LaCoste*, 1956] employed a simple photoelectric measuring system similar to the form used in most instruments of this type. The deflection of the inertia system from a null gave a change in the intensity of the illumination falling on a photocell. A d c servo amplifier was used as a control system. A drift correcting circuit compensated for the electrical drift associated with a d c amplifier. However, the optical system is still subject to drift caused by changes in the photocell and illumination source. Furthermore, in the servo loop, an anticipating or lead network was employed to reduce the hunting. This servo loop performed well if the gain and phase were in proper adjustment, but it has proven to be very critical to these adjustments.

In the development of the second tidal gravity meter, care was taken to overcome both of these major difficulties. The system is now in operation and results are being obtained which indicate that measurements of the variations in gravity can now be made with much less than one microgal error. The two tidal meters have been operated together at Austin, Texas and results indicate a probable error of about 1.25 microgal between the readings of the two instruments when the first instrument is in perfect adjustment.

The gravity meter—The second LaCoste and Romberg tidal gravity meter was constructed in such a manner that it will withstand the rigid field test given commercial gravity meters. Temperature and barometric compensation were obtained to the highest degree of precision. In Figure 1 the data are given for determining the correct thermostating temperature for the meter. Figure 2 shows the response of the meter to an outside change in temperature of more than 23°C. In this test the outside temperature was raised to within five degrees of the operating temperature, and maintained at this temperature for four hours. This is a very severe test, and the smallest temperature effect will show up. The maximum error that could be determined was about 13 microgals. In order to insure that no error due to change in ambient temperature can affect the meter, an outer thermostated heater box is employed, which maintains this outside temperature to approximately ±0.1°C. The pressure test given the meter prior to placing

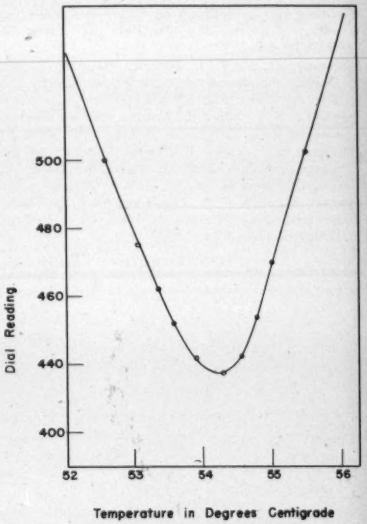

Fig. 1 – Determination of the correct thermostating temperature for tidal gravity meter 2

it in a sealed box is shown in Figure 3. The maximum error for a pressure change of 50 mm of mercury was approximately 15 microgals. The sealed box has a barometer attached to it, and the pressure is maintained constant to less than 0.1 mm. The meter was carefully demagnetized as a safety precaution against changes that might occur

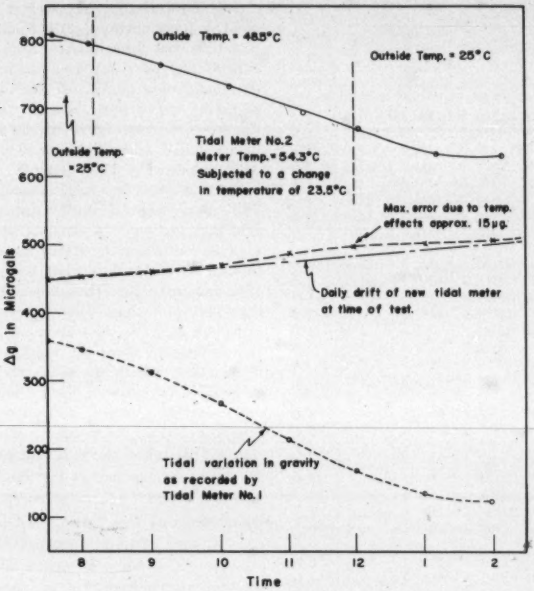

FIG. 2 – Test for temperature effect on tidal gravity meter 2

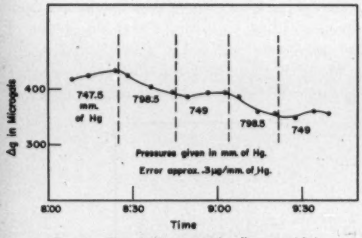

FIG. 3 – Test for barometric effect on tidal gravity meter 2

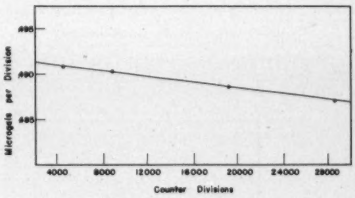

FIG. 4 – Calibration curve for tidal gravity meter 2

in the use of the meter at various locations. Prior to calibration the meter was given a very severe shake test. The meter was then calibrated and checked carefully against a known change in gravity. This calibration curve is shown in Figure 4. In the calibration repeated observations are made at two field stations in the same manner as is done with a regular gravity meter. The results are shown in Table 1. The probable error from this test was 2.6 microgals. We believe these are the most accurate measurements ever obtained with any gravity meter in actual field work.

The drift-free photoelectric optics—The development of drift-free optics to furnish a signal for a self-reading meter was almost a necessity, if full advantage was to be taken of the accuracy of the above described meter. The requirements set on such a system are as follows: (1) The null point or

TABLE 1 – *Results from field test on Tidal Gravity Meter 2*

Field test[a]	Station	Time	Reading	Reading with tidal drift removed	Deviation from mean	Deviation with drift removed
		h m	microgal	microgal	microgal	microgal
1	1	16 07	236.5	236.5	−13.5	−3.5
	2	16 30	4328.7	4329.7	−5.5	1.0
	1	16 40	245.0	247.0	−3.0	1.0
	2	16 50	4327.7	4331.7	−3.5	−2.0
	1	17 02	247.5	253.5	3.5	1.5
	2	17 10	4336.7	4342.7	7.5	3.5
	1	17 20	256.9	262.9	12.9	6.5
	2	17 28	4332.2	4337.2	2.0	7.0
2	1	14 40	12120.3	12120.3	10.1	−3.0
	2	14 52	16193.3	16200.3	11.9	3.0
	1	15 03	12101.5	12113.5	3.3	−1.5
	2	15 11	16173.6	16187.6	−0.8	−2.5
	1	15 20	12081.8	12103.8	−2.4	−1.0
	2	15 27	16154.8	16179.8	−8.6	−4.5
	1	15 35	12076.3	12103.3	−6.9	.2
	2	15 43	16153.8	16185.8	−2.6	7.0
3	2	09 49	11573.7	11573.7	4.8	−1.0
	1	10 00	7497.9	7494.9	3.8	0.0
	2	10 12	11577.2	11570.2	1.3	−1.0
	1	10 21	7501.4	7491.4	1.3	0.5
	2	10 33	11504.9	11567.2	−1.7	−1.0
	1	10 39	7504.9	7488.9	−.2	1.5
	2	10 48	11584.7	11564.7	−4.2	−1.5
	1	10 57	7508.3	7485.3	−4.8	−0.5
4	1	10 49	2228.3	2228.3	−12.7	0.0
	2	11 05	6327.0	6322.0	−6.8	−1.0
	1	11 17	2250.6	2241.6	0.6	1.5
	2	11 25	6335.4	6324.4	−4.4	−6.5
	1	11 36	2269.1	2253.1	12.1	5.0
	2	11 47	6362.8	6340.0	11.2	0.0

Probable error for tests = 2.6 microgals

[a] Work was conducted as follows: Test 1, Dec. 20, 1955; Test 2, Dec. 21, 1955; Test 3, Dec. 22, 1955; Test 4, Dec. 23, 1955.

reading line must be independent of the plate supply voltage functions. (2) The null point should be independent of the characteristics of the photocell. (3) The null point should be independent of the illumination source. (4) The optical system should be symmetrical about the null point. (5) The optics must be able to detect a motion of less than 5×10^{-6} inches. These are all obtained in the optics employed on Tidal Meter 2.

Figure 5 shows the basic fundamentals of the drift-free photoelectric optical system. A beam of light from the source of illumination b is reflected from the mirror a on the gravity responsive system through the double slit c which is so adjusted that equal amounts of light pass through the upper and lower slits when the gravity responsive system is at its null point. As the system moves away from the reading line there will result an increase in illumination through the slit in the direction of motion and a decrease in illumination through the other slit. Disk d (shown in Figure 6) is rotated to interrupt the light beams passing through the two slits, so that half of the time light passes through the upper slit and half of the time through the lower slit before it falls on photocell f. The lower light beam may pass through openings 1 and 1′ and the upper light beam may pass through openings 2 and 2′ as the disk rotates. The light from the two beams is focused as an image of the light source on the photocell f by lens e. A photo sensitive detector h, used to provide a phase reference, is located in such a manner that illumination from source g will fall on it except when the portion of the disk d between R and R″ passes between h and g. Motor m rotates disk d in such a manner that the radius R′r′ always coincides with the dark sec-

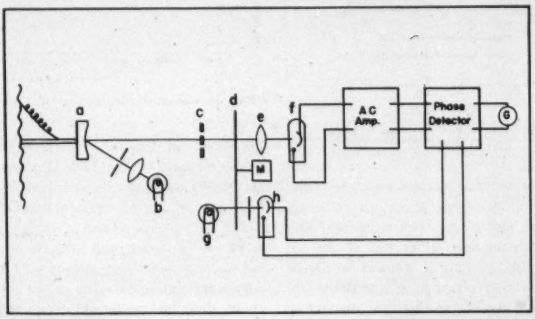

FIG. 5 – Drift-free photoelectric optical system

tion between the double slits c, and the light path gh always passes between the radii R and R″.

From this description it can be seen that when the gravity responsive element is at its null position, the light intensity falling on the photocell is constant because the upper and lower beams are equal. Also, as the gravity responsive element moves away from the null position in either direction, the light intensity varies and the magnitude of the variation is proportional to the deflection from null. The direction of the deflection is determined by the phase of the light variation. Photocell h is used to provide a phase reference and could of course be replaced by a commutator or other device.

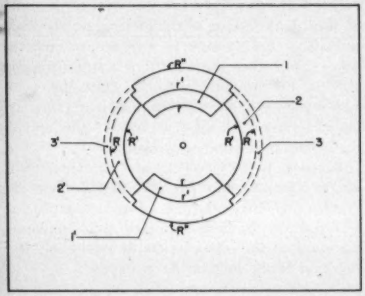

FIG. 6 – Phase-separating disk for optical system

The wiring diagram of the amplifier and phase detector is shown in Figure 7. A 922 photocell P1 is used as the signal detector for the photoelectric optics. A cathode follower gives a low impedance line from the optics to the amplifier. By using a CK5755 for this first stage 20 meg resistors can be employed in the grid circuit and large current amplification is realized. Vacuum tube V2 serves as an a c amplifier and V3 is a cathode follower to isolate the phase detector stage. The signal from photocell P2 controls the bias on V4. This is adjusted so that V4 is cut off when V5 conducts, that is when light falls on P2. However, when P2 is dark V5 cuts off and V4 conducts. Therefore the combination serves as a phase detector since the illumination of the photocell is synchronized with the illumination falling on the sensing photocell. Figure 8 shows the pattern on an oscilloscope placed first across the

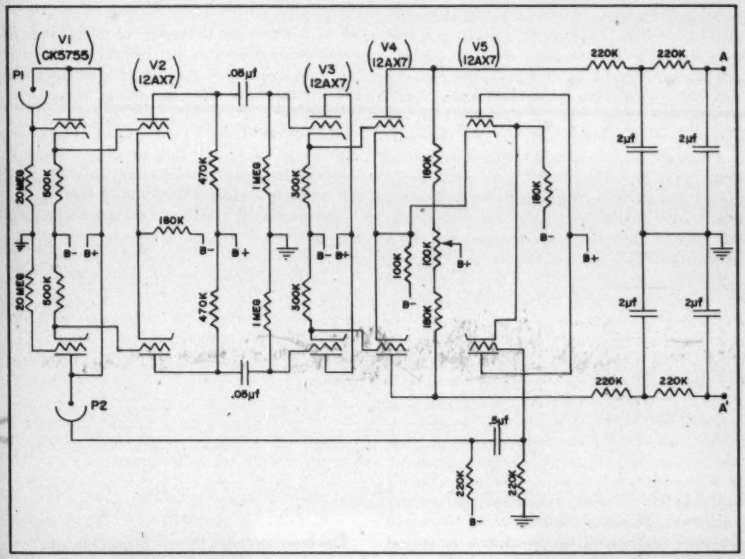

FIG. 7 – Amplifier and phase detector for drift-free photoelectric optical system employed in tidal gravity meter

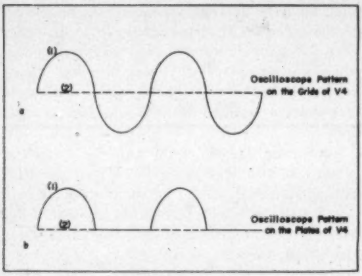

FIG. 8 – Oscilloscope patterns on input and output of the phase detector stage

grids and then across the plates of tube V4. Two cases are shown, (1) when the gravity responsive system is a small distance from the null point, and (2) when the system is at the null point. This rectified signal is averaged and appears across AA′ as a d c signal corresponding to the deflection of the gravity responsive system. The galvanometer in Figure 9 indicates this signal.

The servo-loop—The signal obtained from the phase detector drives the servo-system which controls the position of the gravity responsive system with respect to its null point. The servo turns a selsyn generator which in turn operates a recorder, and thus a self-reading system is obtained. Figure 10 is a block diagram of the control system employed on the tidal gravity meter. Since the meter is a long-period system and critically damped, a simple servo-loop tends to have a degree of hunting associated with it. A compensating network of the type used with the first tidal meter will prevent this hunting but has several limitations. It is basically a differentiating network; thus the damping in the meter enters in as a stiffness effect to the servo motors. Also, the network response is affected by the operations of servo motors. Since this motor operation is often somewhat erratic, an erratic signal is accordingly fed to the network and can result in unstable operation. In the analysis of such a system ideal motors and gears are generally assumed. The inertia term is usually neglected as is the backlash in the gear train; however, in practice these must be accounted for. In order to remove the effect introduced by the motors in the compensating network, a feedback system was employed as shown in Figure 9. In the absence of a compensating circuit, the signal from the optical system drives the positioning motor which turns the measuring screw in such a manner as to position the beam at the null point, but, because of the long period of the gravity meter, the servo will over-shoot and hunting will result. In order to prevent this, the positioning motor drives not only the measuring screw but also the moving contacts on the potentiometers (shown in Figure 9) in such a manner as to feed back a negative signal proportional to the angle through which this motor turns. This signal has a time constant of the order of the time constant of the meter, and the compensating circuit output is adjusted to stop the servo motor when the correction is approximately right. If the correction is exactly right, the operation is complete; if not, other small corrections are made after the delayed actions in the gravity meter and compensating networks.

Referring to the servo-loop used in the first tidal meter [*Clarkson* and *LaCoste*, 1956], where the gravity responsive system is critically damped and an error-rate or differentiating circuit is employed, we obtained the following transfer function as a function of the angular frequency ω

$$Y(j\omega) = \frac{G\omega_0^2}{(j\omega)\left(\frac{\alpha + j\tau\omega}{1 + j\tau\omega}\right)(\omega_0 + j\omega)^2}$$

where α is the ratio of the sum of the resistors to the shunting resistor in the error-rate circuit, τ is the time constant of the parallel condenser and resistor, ω_0 is 2π times the natural frequency of the system, and G is the gain in the system.

The servo loop used in the second tidal meter is shown in Figure 11b. In discussing it the inner loop will first be omitted and then its effect on the complete system will be considered.

The differential equation of the outer servo-loop only is

$$\ddot{\theta}_o + 2r\dot{\theta}_o + \omega_0^2\,\theta_o = \omega_0^2 G \int \epsilon\, dt, \quad \epsilon = \theta_i - \theta_o$$

where $2r$ is the ratio of the damping factor to the mass of the gravity meter, θ_i is the input to the system and θ_o is the output. This gives a transfer function

$$Y(j\omega) = \frac{G\omega_0^2}{(j\omega)|(\omega_0^2 - \omega^2) + 2rj\omega|}$$

Now for $r = \omega_o$ (critically damped)

$$Y(j\omega) = \frac{G\omega_0^2}{(j\omega)(\omega_0 + j\omega)^2}$$

The inner feedback loop of Figure 11b will now be considered. The lower block in this loop is

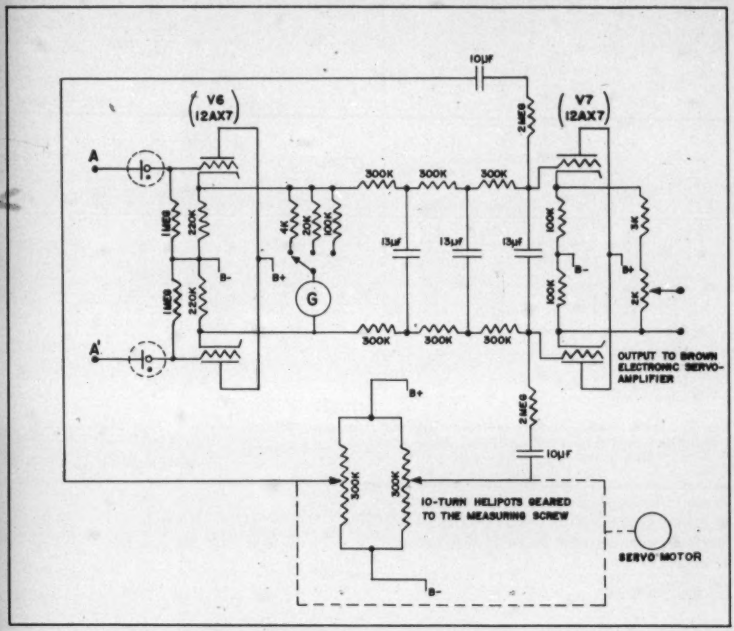

FIG. 9 – Servo compensating network and microseismic filter for drift-free photoelectric optical system

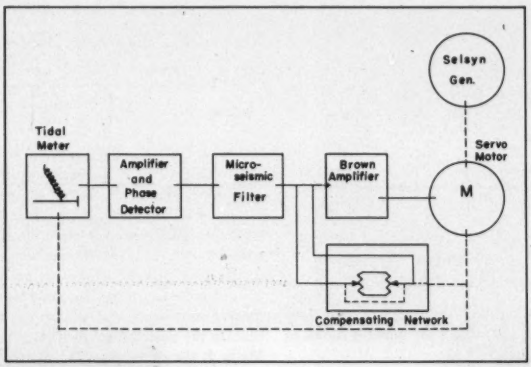

FIG. 10 – Control system for tidal gravity meter employing drift-free photoelectric optical system

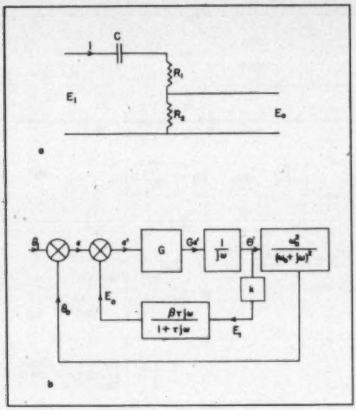

FIG. 11 – Block diagram of servo control for LaCoste and Romberg tidal gravity meter 2; (a) the lower block in the loop; (b) the loop

shown in Figure 11a where E_i is the input voltage to it and E_o is the output voltage. The transfer function for the circuit of Figure 11a can be found as follows

Let $R = R_1 + R_2$

$$\beta = \frac{R_2}{R_1 + R_2}$$

$$\tau = RC$$

Then

$$E_o = iR_2$$

and

$$\frac{dE_i}{dt} = \frac{i}{C} + R_1\frac{di}{dt} + R_2\frac{di}{dt} = \frac{E_o}{R_2C} + \frac{R_1 + R_2}{R_2}\frac{dE_o}{dt}$$

which gives

$$\left[\left(\frac{R_2}{R_1 + R_2}\right)RC\frac{d}{dt}\right]E_i = \left[1 + RC\frac{d}{dt}\right]E_o$$

or

$$\frac{E_o}{E_i} = \frac{\beta\tau d/dt}{1 + \tau d/dt}.$$

We will now consider the complete servo-loop shown in Figure 11b. Using the symbols shown in Figure 11b, we have

$$\epsilon' = \epsilon - E_o$$

$$E_o = \frac{j\beta\tau\omega}{1 + j\tau\omega}E_i$$

$$E_i = k\theta'$$

$$\theta' = \frac{G\epsilon'}{j\omega}$$

Therefore

$$\epsilon' = \epsilon - \frac{\beta\tau j\omega}{(1 + \tau j\omega)} \times \frac{kG\epsilon'}{j\omega}$$

Or

$$\epsilon = \epsilon' + \frac{\beta\tau kG\epsilon'}{1 + \tau j\omega}$$

Now

$$\theta_o = \frac{\omega_0^2}{(\omega_0 + j\omega)^2}\theta'$$

Therefore

$$\theta_o = \frac{G\epsilon'\omega_0^2}{(j\omega)(\omega_0 + j\omega)^2}$$

And

$$\epsilon' = \frac{1 + \tau j\omega}{[(1 + \beta\tau kG) + \tau j\omega]}\epsilon$$

Giving

$$\theta_o = \frac{G\omega_0^2}{(j\omega)\left[\dfrac{(1 + \beta\tau kG) + \tau j\omega}{1 + \tau j\omega}\right](\omega_0 + j\omega)^2}\epsilon$$

Let

$$\alpha = 1 + \beta\tau kG$$

Then we have as a transfer function

$$Y(j\omega) = \frac{G\omega_0^2}{(j\omega)\left[\dfrac{\alpha + j\tau\omega}{1 + j\tau\omega}\right](\omega_0 + j\omega)^2}$$

This is the same form of transfer function that was obtained with the servo system employed with Tidal Meter 1. Consider the inner loop consisting of the amplifier, motor, and feedback, and we have in effect a lead network. From a theoretical consideration these two systems appear to function in the same manner. However, we must consider the difference in the two methods used in obtaining these results and the assumptions made in each case. In the case of the error-rate system used with Meter 1, the effect depends directly on the signal

TABLE 2 – *Results of simultaneous measurements*

Date	C.S.T.	Tidal Gravity Meter		Difference	Mean deviation
		No. 1	No. 2		
1956	h m	microgal	microgal	microgal	microgal
Sep. 12	11 00	198	195	3	−1.5
	12 00	232	228	4	−0.5
	13 00	239	236	3	−1.5
	14 00	256	252	4	−0.5
	15 00	265	262	3	−1.5
	16 00	269	266	3	−1.5
	17 00	268	264	4	−0.5
	18 00	263	259	4	−0.5
	19 00	258	253	5	0.5
	20 00	256	250	6	1.5
	21 00	256	250	6	1.5
	22 00	259	253	6	1.5
	23 00	265	259	6	1.5
	24 00	269	263	6	1.5
Sep. 13	01 00	271	265	6	1.5
	02 00	265	262	3	−1.5
	03 00	254	250	4	−0.5
	04 00	237	234	3	−1.5
	05 00	220	215	5	0.5
	06 00	199	196	3	−1.5
	07 00	182	179	3	−1.5
	08 00	174	169	5	0.5
	09 00	174	168	6	1.5
	10 00	185	179	6	1.5
	21 00[a]	285	280	5	1.6
	22 00	284	279	5	1.6
	23 00	291	286	5	1.6
	24 00	302	298	4	0.6
Sep. 14	01 00	313	309	4	0.6
	02 00	320	317	3	−0.4
	03 00	321	317	4	0.6
	04 00	313	309	4	0.6
	05 00	392	289	3	−0.4
	06 00	270	265	5	1.6
	07 00	241	239	3	−0.4
	08 00	221	217	4	0.6
	09 00	210	205	5	1.6
	10 00	210	205	5	1.6
	11 00	224	220	4	0.6
	12 00	250	245	5	1.6
	13 00	284	280	4	0.6
	14 00	321	317	4	0.6
	15 00	349	346	3	−0.4
	16 00	368	365	3	−0.4
	17 00	372	370	2	−1.4
	18 00	363	361	2	−1.4
	19 00	345	343	2	−1.4
	20 00	325	323	2	−1.4
	21 00	308	306	2	−1.4
	22 00	301	298	3	−0.4
	23 00	304	302	2	−1.4
	24 00	319	317	2	−1.4
Sep. 15	01 00	340	336	4	0.6
	02 00	358	356	2	−1.4
	03 00	372	369	3	−0.4
	04 00	372	370	2	−1.4

TABLE 2 – *Continued*

Date	C.S.T.	Tidal Gravity Meter		Difference	Mean deviation
		No. 1	No. 2		
1956	h m	microgal	microgal	microgal	microgal
Sep. 15	05 00	360	357	3	−0.4
	06 00	336	333	3	−0.4
	07 00	304	302	2	−1.4
	08 00	272	270	2	−1.4
	09 00	246	244	2	−1.4
	10 00	238	234	4	0.6
	11 00	244	240	4	0.6
	12 00	268	264	4	0.6
	13 00	304	299	5	1.6
	14 00	345	340	5	1.6
	15 00	382	378	4	0.6
	16 00	407	403	4	0.6
	17 00	417	415	2	−1.4
	18 00	410	406	4	0.6
	19 00	387	385	2	−1.4
	20 00	360	357	3	−0.4
	21 00	332	329	3	−0.4
	22 00	316	314	2	−1.4
	23 00	316	312	4	0.6
Sep. 16	09 00[b]	198	194	4	0.1
	10 00	178	173	5	1.1
	11 00	175	170	5	1.1
	12 00	190	185	5	1.1
	13 00	225	220	5	1.1
	14 00	268	263	5	1.1
	15 00	313	309	4	0.1
	16 00	350	344	6	2.1
	17 00	368	363	5	1.1
	18 00	366	360	6	2.1
	19 00	345	339	6	2.1
	20 00	308	304	4	0.1
	21 00	273	270	3	−0.9
	22 00	246	244	2	−1.9
	23 00	236	233	3	−0.9
	24 00	244	240	4	−0.1
Sep. 17	01 00	270	266	4	−0.1
	02 00	305	302	3	−0.9
	03 00	340	338	2	−1.9
	04 00	365	364	1	−2.9
	05 00	373	372	1	−2.9
	06 00	360	358	2	−1.9

Probable error = 1.24 microgals

[a] The level lights on No. 1 were accidentally left on for several hours and no data were obtained until 21h 00m.

[b] Data were not obtained from 23h 00m to 09h 00m because of an error in the level of meter 1 that occurred around 24h 00m.

obtained from the gravity responsive system, whereas in the feedback system used with Meter 2 the signal is obtained from the drive to the gravity responsive system and is independent of the response this system has to the motor drive. Any

variation in the response or asymmetry in motor drive produces errors in the first system, but does not affect the second system.

Simultaneous observations with Meters 1 and 2—In order to compare and check the accuracy of the tidal gravity meters developed at LaCoste and Romberg, simultaneous measurements of the tidal variations in gravity at Austin, Texas were made with the two instruments. Observations were made over a period of five days prior to sending Meter 2 out of the laboratory for observations in the Hawaiian Islands. During this time the long-period drift of the two instruments appeared to be very nearly the same, and therefore no drift was removed from either instrument. The meters had been carefully calibrated between stations that were well established by LaCoste and Romberg land gravity meters, and the calibration factors are good to at least one part in a thousand. Since the maximum tidal variation in gravity is less than 300 microgals, any calibration error should not enter into the results.

In Table 2 the results of the simultaneous observations are given. The difference and mean deviation for each reading are shown. The probable error between the readings of the two meters was 1.24 microgals. If this is considered the sum of the errors of the two meters then each meter is probably accurate to better than one microgal. However, from the observation of the performance of the two instruments, it appears that most of this error can probably be attributed to the first meter. In the case of Meter 2, no errors were ever detected in any of the observations or in any performance of the system. On the other hand, Meter 1 is subject to various performance errors, one of which is in the servo-system which incorporates a d c amplifier and d c motors. The characteristics of these motors are affected by their operating conditions. The electrical drift compensating circuit will correct for a limited rate of linear electrical drift; however, under certain conditions this may be exceeded and errors will occur. In addition to these expected errors, Meter 1 had just been put back into operation after an overhaul, and the level adjustments were more critical because of the seating of the leveling screws on the concrete pillar on which it rests.

It seems apparent from this data and the observations of the performance of the instruments that Tidal Meter 2 with the drift-free electrical optics and improved servo-system can be relied on to measure tidal variations in gravity with an accuracy of much better than one microgal.

The measurement of "Earth tides"—The LaCoste and Romberg Gravity Meter Co. developed this tidal meter for use by the Institute of Geophysics at UCLA in a world-wide survey of the tidal variation of gravity. The instrument will be on loan to this Institute for use during the Geophysical Year. The results of these measurements should give much-needed information concerning the Earth tides throughout the world.

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LaCoste and Romberg, 6606 North Lamar Blvd., Austin 5, Texas

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Observed and Computed Radiation from First to Fourth Contact during a Total Solar Eclipse

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Abstract—A comparison is given of the observed and the computed solar radiation received on a horizontal surface throughout an eclipse in Brazil in 1947. The radiation was measured with an Eppley pyrheliometer, standardized by the Astrophysical Observatory of the Smithsonian Institution.

The ratio R_t/R_0 is the computed radiation at time t referred to the radiation R_0 at first contact.

$$R_t/R_0 = ab(\sin \alpha_t/\sin \alpha_0)p^{(\sec z_t - \sec z_0)}$$

where a is the fractional area of the Sun's disk not covered by the Moon; b is a correction factor (ranging from 1.02 to 0.7) to account for the diminution in brightness of the solar disk as the limb is approached; $\sin \alpha$ gives the vertical component of the radiation on a horizontal surface for a solar altitude α; p is the transmission coefficient, taken as 0.8 (altitude 2200 ft); z is the zenith angle; sec z gives the air mass.

The results are given in a graph, extending from first to fourth contact. The observed and computed values of the radiation are in close agreement.

Introduction—Solar radiation measurements during a total eclipse are of special interest because they provide an opportunity to compare the observed and computed radiation through a wide range in intensity, during a relatively short time interval. For such a comparison, it is desirable that the altitude of the Sun should be high, both at the beginning and end of the eclipse (1st to 4th contact).

The expedition of the National Geographic Society and the Air Force to Bocaiuva, Brazil, to observe the solar eclipse of May 20, 1947 afforded an exceptional opportunity for such a study. The eclipse began at 08 h 22 m and ended at 11 h 01 m local time, lasting about 2¾ hours. The skies were clear throughout, save for a few cirrus clouds. So far as the writer knows, this is the first time that the solar radiation has been measured from first to fourth contact, under favorable conditions throughout, and compared with computed values. A similar study was made by the Blue Hill Meteorological Observatory[1] [*Brooks* and others, 1941, p. 20] during the solar eclipse of 1932, but some clouds were present and totality occurred so late in the afternoon that the second branch of the radiation curve was dwarfed.

Apparatus used—The observations in Brazil were made with an Eppley pyrheliometer (#1457, 10-junction) loaned for the purpose through the courtesy of the Astrophysical Observatory of the Smithsonian Institution. This instrument receives the radiation from the Sun and the entire hemisphere of the sky on a flat horizontal surface located at the center of a spherical glass envelope. The receiving element is divided into a central disk surrounded by two concentric rings, all insulated from one another. The inner disk and the outer ring have white surfaces. The surface of the intermediate ring is black. One junction of each thermocouple is attached to the under side of the black ring, the other to the under side of the white disk. The differential temperature of the two parts is thus measured, which is taken to be proportional to the quantity of heat being absorbed per unit time by the blackened surface.

The electromotive force developed by the ten thermo-junctions in series was measured directly by a Leeds and Northrup precision potentiometer sensitive to one microvolt. Readings were customarily made to the nearest five microvolts. The mean of three readings was taken to represent the observation. The calibration constant provided by Eppley Laboratories for Pyrheliometer 1457 was 1.79 millivolts per gram-calorie per minute per square centimeter, assuming a linear relationship through the range 0.600 to 1.114 calories (mean of 75 comparisons with the standard). Consequently five microvolts corresponds approximately to a precision of 0.003 gram-calorie.

Measurements—Measurements were made at hourly intervals for a number of days preceding the eclipse, by members of the Air Force Meteorological Section under the direction of Wm. E. Walls. During the actual period of the eclipse, observations were taken at intervals of three to five minutes.

The radiation at noon on May 20 (eclipse day) was 1.29 cal/cm²/min., which was a little below

normal. The noon radiation on four preceding days, May 8 to 11 inclusive, was in every instance between 1.36 and 1.38 cal/cm²/min. One-half of the difference is accounted for by the change in the sun's altitude during the intervening ten days.

It may be of interest to note that at night the pyrheliometer gave small but measurable negative readings. In other words at night the radiation was to the sky.

Correction for non-uniform distribution of radiation over the solar disk—The weather conditions on the day of the eclipse were so favorable, permitting complete observations from first to fourth contact, that it was decided to include, in the computed value of the radiation received at a given time, a term representing the non-uniform distribution of energy over the Sun's disk. To determine this, the Sun's disk was divided into five circular zones of equal area, bounded by the solid lines in Figure 1. From various sources [*Swartzchild* and Villiger, 1906; Very, 1902]. I computed the relative brightness of the five zones, starting from the center, with the following results: 1.24; 1.17; 1.03; 0.89; 0.67. The mean is, of course, unity. I also computed the relative zonal intensity from data given by *Abbot* [1926] on the distribution of energy over the Sun's disk for wave length 5955A, with the following results: 1.23; 1.14; 1.05; 0.91; 0.68. Insofar as the final results are concerned, these ratios are in practical accord with those given above.

The passage of the Moon over the Sun's disk from first to second contact was also divided into ten equal time intervals of about seven minutes each, represented by the broken circles in Figure 1. An area represented by a given time interval usually included contributions from five zonal (k) regions. Thus for an area A_n representing time interval n we have

$$A_n = k_1 + k_2 + k_3 + k_4 + k_5$$

These areas were measured individually with a planimeter and were then multiplied by a common factor such that $\sum^{10}{}_1 A_n = 1000$ units of area.

The procedure was then repeated, weighting each zonal area with its appropriate brightness factor.

$$W_n = 1.24k_1 + 1.17k_2 + 1.03k_3 + 0.89k_4 + 0.67k_5$$

where $\sum^{10}{}_1 W_n = 1000$ units of area times brightness.

The sum of the first three A areas, for example, represent a totality of 19 pct for a Sun of uniform brightness, and an exposed area of 81 pct. The corresponding W areas show that owing to the zonal weighting the totality on a radiation basis is 17.5 pct. leaving an exposed area of 82.5 pct.

The ratio 82.5/81 = 1.02 is the brightness factor b which must be applied to the exposed area (computed geometrically) to give the actual radiation. At the end of the successive nine time intervals, b was found to be 1.01; 1.02; 1.02; 1.01; 0.99; 0.96; 0.91; 0.82; 0.70.

A more detailed and precise calculation of eclipse areas has been made by *Beard* [1948] of the Naval Research Laboratory. This was not available at the time these computations were made.

Computation of the radiation received during the progress of the solar eclipse—The radiation received on a horizontal surface at a given time during the progress of an eclipse is given by

$$R_t = Rab \sin \alpha p^{\sec z} \qquad (1)$$

Where R is the radiation received when the Sun is at the zenith

a is the fractional area of the Sun's disk not covered by the Moon

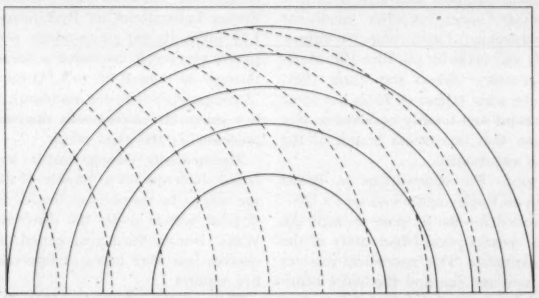

FIG. 1 – Chart used to correct for the decrease in brightness of the solar disk from center to limb; Moon moves from left to right across the Sun

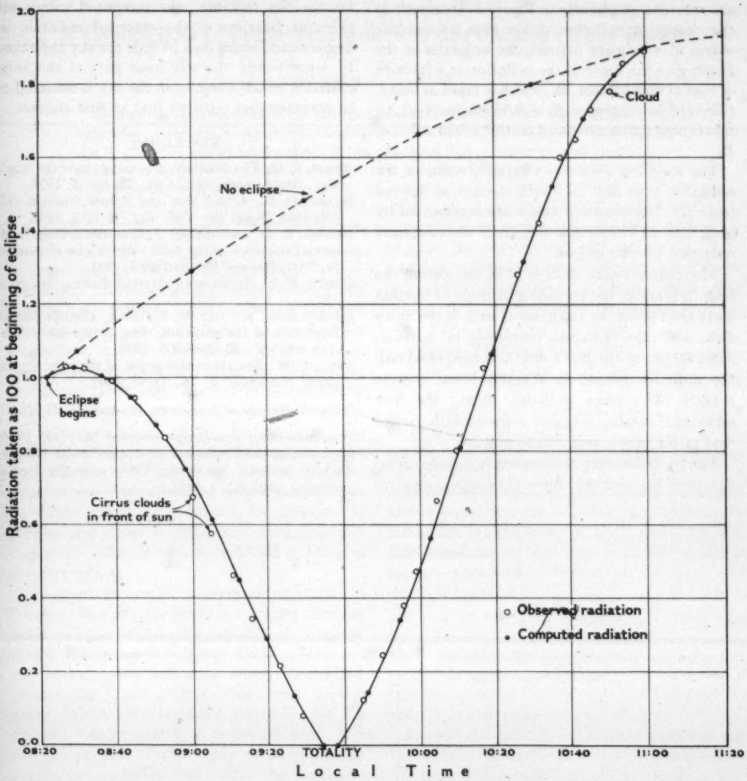

FIG. 2 – Comparison of the observed and computed radiation received on a horizontal surface during a solar eclipse

b is the correction factor for brightness
α is the angular altitude of the Sun
$\sin \alpha$ is the vertical component of the radiation on a horizontal surface
p is the transmission coefficient, taken as 0.8 (altitude 2250 ft)
z is the zenith angle
$\sec z$ is the air mass

We are here primarily interested in the ratio of the radiation R_t to R_0, the radiation at first contact, or

$$\frac{R_t}{R_0} = ab \frac{\sin \alpha_t}{\sin \alpha_0} p^{(\sec z_t - \sec z_0)} \qquad (2)$$

The required astronomical data were found in the American Ephemeris for 1947.

The altitude of the observing station at Bocaiuva was about 2250 ft, and the transmission coefficient p at this altitude was assumed to be 0.80. This represents the transmission when the Sun is in the zenith (sec z = 1). The average transmission for wavelengths 0.38 μ to 0.8 μ inclusive at a height of one mile is given by the Astrophysical Observatory [*Fowle*, 1932, p. 608] as 0.82. For an air mass greater than unity, we have a transmission coefficient of $0.8^{\sec z}$.

The values obtained for the observed and computed radiation during the course of the eclipse

are recorded graphically in Figure 2. Inasmuch as the change in radiation, rather than its absolute value, is of primary interest, the ordinates of the graph give the value of the radiation as a fraction of that at first contact, R_0, which is taken as unity. (The absolute value of $R_0 = 0.66$ cal/cm^{2}min) All subsequent ratios are based on this initial value of R_0.

The solid line gives the computed value of the radiation from first to fourth contact as derived from (2). The observed values are represented by open circles. The broken line gives the computed radiation with no eclipse.

The eclipse began at 08 h 22 m but during the first 15 minutes the increasing altitude of the Sun more than offset the reduction in area of the Sun's disk, and the radiation continued to increase. After 40 pct of the Sun's disk had been obscured, the radiation fell off in a nearly linear way to totality. The mean radiation during the four minutes of totality was only a thousandth part of that of the unobscured Sun at midday.

The pyrheliometer measurements include radiation from Sun and sky. While (1) contains no term for the sky radiation, the computed values are given as fractions of the observed radiation at first contact, which does include the sky radiation. In other words, the fractional part of the total radiation which comes from the sky is assumed to be constant and equal to that at first contact.

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A Comparison of Some Approaches to the Diabatic Wind Profile

WILLIAM P. ELLIOTT

Abstract—Several expressions for the wind profile in diabatic flow were compared with each other. Although the forms compared appear quite different, it was found that a great deal of similarity existed among them. It was concluded that accuracy of wind observations will have to be improved before it can be stated conclusively that one expression best describes the observed profiles.

Introduction—The concept of the mixing length was introduced into micrometeorology as a means of describing the wind profile near the surface of the Earth. The logarithmic wind profile which this concept predicts has been found to be a quite adequate description of flow in an adiabatic atmosphere near a relatively homogeneous surface. However, departures from the logarithmic profile are frequently observed in non-adiabatic (diabatic) flow, most notably on clear days in the afternoon when the temperature lapse rate near the surface may be distinctly super-adiabatic and with nocturnal inversions. Various modifications of the original mixing length formulations have been introduced to account for the observed profiles and these modifications have generally included a term dependent upon the stability of the atmosphere.

In connection with another investigation, it became necessary to choose a form for the diabatic mixing length. Expressions of *Holzman* [1943], *Halstead* [1954], *Lettau* [1949, 1952], and the author, (and indirectly *Rossby* and *Montgomery* [1935], and *Deacon* [1949]) were investigated. While an alternative expression for the diabatic mixing length is presented here, it is not the purpose of this study to advocate any particular expression but rather to emphasize the similarities among the existing forms.

Comparison of mixing lengths—Rossby and *Montgomery* [1935] have derived an equation for the mixing length under stable conditions. This derivation considers the influence of thermal stability on the mixing length. Under stable conditions their equation has the form

$$l_s = l/\sqrt{1 + S\,Ri} \tag{1}$$

where l_s = mixing length under stable conditions

l = adiabatic mixing length = $k_0 z$

Ri = Richardson number = $(g/\theta)(\partial\theta/\partial z)/(\partial u/\partial z)^2$

S = non-dimensional positive constant

A number of authors have pointed out that (1) requires that Ri approach infinity before l_s approaches zero and also that negative values of Ri may lead to imaginary l_s. Since it appears that turbulence is suppressed at finite values of Ri, other forms for l_s have been sought.

Holzman [1943] suggested a form

$$l_s = l(1 - S\,Ri)^{\frac{1}{2}} \tag{2}$$

This form has the advantages that $l_s = 0$ at a finite value of $Ri(= 1/S)$ and that it can be extended to unstable conditions without l_s becoming imaginary.

If the terms $1/(1 + S\,Ri)^{\frac{1}{2}}$ and $(1 - S\,Ri)^{\frac{1}{2}}$ are expanded in series, the first two terms of the expansions are the same and equal to $1 - S\,Ri/2$ (this expansion is valid only if $(S\,Ri)^2 < 1$). It appears reasonable therefore to try a mixing length of the form

$$l_s = l(1 - S\,Ri/2) \tag{3}$$

which embodies the advantages of (2), does not lead to imaginary values of l_s, and is a better approximation to both (1) and (2) than are (1) and (2) to each other, for $(S\,Ri)^2 < 1$.

In order to test (3) a different expression for the velocity profile derived by *Halstead* [1954] was used. This profile equation is unique in that the physical reasoning from which it is derived differs from the classical approach, although there are underlying similarities not immediately obvious.

Halstead considers distortion of streamlines or 'stream surfaces' as a physical description of turbulent flow. An expression for the transfer of momentum (stress) is obtained in terms of the viscosity, the wind shear, the height of the laminar sub-layer and a distortion factor which is evaluated from experimental data. Turbulent flow over a rough surface is treated as though each roughness element subtracted a certain amount of momentum, which amount is expressed as a 'drag velocity.' A non-dimensional buoyancy

factor b is introduced into the diabatic equation. The profile equation finally obtained is

$$u + u_s = u_\delta[1 + (1/r) \ln z/(\delta + bz)] \quad (4)$$

where u = velocity above the laminar sub-layer

u_δ = velocity at top of laminar sub-layer = $\sqrt{\tau/\rho}/0.0861$

δ = thickness of the laminar sub-layer

b = buoyancy factor (non-dimensional)

r = per cent increase in area due to turbulent distortion of a single layer = 4.65 from experimental data

u_s = velocity decrease, or 'drag velocity', due to roughness elements [= $u_\delta(1 + (1/r) \ln z_0/\delta)$]

z_0 = roughness parameter

Substitution of the expressions for u_δ and u_s into (4) leads to

$$u = (\sqrt{\tau/\rho}/k_0) \ln z/z_0[1 + (b/\delta)z] \quad (5)$$

k_0 = von Karman's constant

The profile equation in this form reduces to the familar adiabatic equation when $b = 0$. By differentiation of (5) a mixing length can be obtained

$$l_e = k_e z[1 + (b/\delta)z] \quad (6)$$

In order to test the hypothesis that (3) and (6) are essentially the same, the two expressions can be equated and the resulting equation solved for S. Thus

$$S = -(2b/\delta)z/Ri \quad (7)$$

Data taken by *Halstead* [1954] at the Great Plains Turbulence Field Program, O'Neill, Nebraska, give values of b/δ and corresponding Richardson numbers for a height of 40 cm. Evaluation of S by means of (7) gives a mean value of 7.2. *Deacon* [1949] computed a mean value of $S = 7.1$ over short grass and desert conditions using the Holzman form for the mixing length. Deacon's value is a mean of fifteen observations while the value from Halstead's data is the mean of almost two hundred observations representing conditions at each hour of the day.

Lettau [1952] has also found a mean value of S in the Holzman equation to be about seven for average inversional conditions although his analysis shows a dependency upon stability.

Eq. (2) can also be equated with (6) and solved: $S = -(2b/\delta)(z/Ri) - (bz/\delta)^2(1/Ri)$. The additional term leads to a mean value of S only slightly less (about 7.0) in the range of the data than (7). (It can be seen that one of the differences between (2) and (3) lies in the critical Richardson numbers that come from them. Eq. (2) leads to a value of 0.14 while (3) leads to a value of 0.28. This latter value is in close agreement with the mean value of 0.3 computed by *Glaser* [1952] from data taken at Brookhaven, and the value 0.25 computed by *Taylor* [1931].)

Thus, while the above comparison does not conclusively establish the validity of any of these three mixing lengths, the fact that different reasoning leads to roughly the same conclusion is indeed interesting.

A reason for preferring (3) to (2) can be found in an examination of the profiles resulting from these two assumptions. Both equations can be readily integrated if Ri is assumed to vary linearly with height, an assumption borne out by several studies [see, for example, *Deacon*, 1949].

Assuming $Ri = Az$ the profile equation can be written

$$u = \int_{z_0}^{z} [\sqrt{\tau/\rho}/k_0 z(1 - \alpha z)]\, dz \quad (8)$$

$$= (\sqrt{(\tau/\rho)}/k_0) \ln [(z/z_0)\,(1 - \alpha z_0)/(1 - \alpha z)]$$

where $\alpha = SA/2$

This appears to be a quite rational form for the profile, particularly since $\alpha z_0 \ll 1$ in general. Also (8) reduces to the familiar adiabatic profile when $\alpha = 0$.

Under these same conditions (2) leads to a profile of the form

$$u = \sqrt{(\tau/\rho)}/k_0 \ln \left\{ \frac{\sqrt{1 - 2\alpha z} - 1}{\sqrt{1 - 2\alpha z} + 1} \cdot \frac{\sqrt{1 - 2\alpha z_0} + 1}{\sqrt{1 - 2\alpha z_0} - 1} \right\} \quad (9)$$

This form is unduly clumsy and indeterminate when $\alpha = 0$.

Deacon [1949] has suggested a form

$$\partial u/\partial z = az^{-\beta} \quad (10)$$

where a and β are constant and

$$\beta > 1 \qquad Ri < 0$$

$$\beta = 1 \qquad Ri = 0$$

$$\beta < 1 \qquad Ri > 0$$

Lettau [1949] has suggested, from still other

considerations, that l_s may be written as follows

$$l_s = l/(1 + x)$$

or approx. $l_s = l(1 - x)$, $(x^2 < 1)$

where $x = (\partial u/\partial z)^2/(\partial u/\partial z)_a^2 \cdot Ri$

$(\partial u/\partial z)$ is the diabatic wind shear and $(\partial u/\partial z)_a$ is the adiabatic wind shear.

Lake [1952] has compared these two forms and, after considerable algebraic manipulation, arrived at a graph showing the dependence of β on the Richardson number. In an analysis similar to Lake's the ratios of the wind shear at two levels z_1 and z_2 (a small distance apart), as determined from (10) and (3), were equated. Taking the limit as z_2 approaches z_1 led to an expression

$$\beta = 1 - (S\,Ri/2)/(1 - S\,Ri/2) \qquad (11)$$

Figure 1 shows a plot of β versus Ri using (11) with $S = 7.0$. The plot of β versus Ri from Lake is shown for comparison. The agreement between the two curves is very good in the unstable region and up to Ri about 0.025 where the two curves begin to diverge. Certainly the agreement between these curves indicates that the assumptions of Lettau and the basis for (3) do not lead to radically different results when compared in this manner over most of the range of Ri shown in Figure 1.

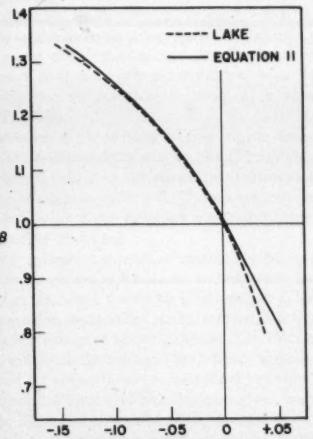

FIG. 1 – Theoretical variation of Deacon's exponent β with Richardson's number Ri

Discussion of assumptions—All throughout this discussion S has been assumed constant. Deacon found no systematic variation of S with either stability or roughness parameter, but the solutions of (7) using Halstead's data indicate the possibility of a slight decrease of S with increasing stability. This could reflect imperfect assumptions such as Ri may not vary linearly with height, and Halstead's b term may depend slightly on height.

It should be further pointed out that the Richardson number used in the discussion is a localized Richardson number and the form used here is not a unique expression for this parameter. For instance, the localized Ri, which varies from place to place in the flow, cannot be used as a modelling parameter. We have allowed Ri to vary with height and have, in fact, assumed that this variation is linear; however, if a gross Richardson number was used to describe the entire flow pattern, as the Reynolds number is used in some cases, then we would be led to a value of S which is a function of height. The role of the Richardson number in atmospheric problems has been discussed by *Batchelor* [1953] where he establishes the validity of the assumption that this number is a governing parameter for the type of flow considered here. (It is the author's feeling that this paper should be read by all who deal with Richardson numbers in atmospheric problems.)

Conclusions and summary—We have seen above that a number of different expressions for the diabatic mixing length are to be found. However, close comparison by means of certain indirect means have indicated that there is a marked similarity of results stemming from these different assumptions. If the simple logarithmic profile is taken as the first order approximation and the various expressions for the effect of buoyancy, discussed above, as second order approximation, we will, in general, have to go to the third order to find much difference of opinion. (Such a third order difference might be a variable coefficient of Ri similar to that suggested by Lettau.) If this is true, as it appears to be, it is an encouraging fact, for it indicates that a convergence upon the solution of one of the fundamental micrometeorological problems is taking place.

The improvement in micrometeorological instrumentation may soon reach the point where these differences can be investigated but at present it is difficult to go beyond the second order with most sets of published data. However, future studies of both wind and temperature

profiles must take into account variations in both stability and the effect of elevation on stability.

Acknowledgments—The author would like to express thanks to Maurice Halstead, Department of Oceanography and Meteorology, Texas A & M, for first suggesting this problem, and to Heinz Lettau, AFCRC, and Arnold H. Glaser, Department of Oceanography and Meteorology, Texas A & M, for reviewing the manuscript and offering many helpful suggestions.

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Estimation of the Heat-Transfer Coefficient Between Air and the Ground Surface

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Abstract—For the purposes of programming a computer to predict the depths of freezing and thawing in soils, a simple method is outlined with the appropriate charts for calculating the value of the surface heat-transfer coefficient, based on meteorological information which is normally easily obtainable. All the significant parameters are included, and an account of the investigation leading to the preparation of each chart is given.

Introduction—The author was employed on a research project sponsored by the Arctic Construction and Frost Effects Laboratory, U. S. Corps of Engineers, New England Division, at the Massachusetts Institute of Technology. The object of the research program was to design and construct an hydraulic analogue computer (R. F. Scott, unpublished thesis, Dept. of Civil and Sanitary Engineering, MIT, 1955) for predicting the depths of freezing and thawing in soils in Arctic and subarctic areas, since such information is of great importance to the design of airfields, highways, and various types of buildings in cold climates. However, when the construction of the computer was already well-advanced, it became obvious that a pressing problem existed in the determination of the various heat fluxes at the air-soil interface which result in the transfer of heat into or out of the ground. This paper presents the results of the investigation which took place, and which was based on the analysis of various published data on micrometeorological measurements. The procedure followed is thus largely an empirical one. The investigation is described in detail in a report [*MIT*, 1956].

Statement of the problem—The analogue computer, for one-dimensional studies, as built, represents at various points in the apparatus, temperatures at various depths in the soil. There is consequently one end point which describes the temperature at the surface of the soil.

Only a limited amount of meteorological information is generally available for arbitrary locations in the North American Continent, and, however meager, must suffice for at least rough estimations of freezing or thawing depths. This information will generally consist of the latitude and elevation of the chosen place, some annual variation of temperature and wind velocity at a given height in the air, together with humidity fluctuations and some data on percentage possible sunshine or cloud cover. Usually the roughness of the soil, or, say, airfield surface will also be known. From knowledge of some of the above factors, the amount of incoming radiation to the soil surface can be calculated to an accuracy at least as good as that of the other quantities involved. The amount of longwave outgoing radiation depends on the surface temperature, on the vapor pressure and air-temperature profiles, and on the cloud cover according to known equations, but an estimation of its magnitude awaits the determination of the surface temperature. When an airfield pavement is concerned, the heat loss due to evaporation can probably be calculated with sufficient accuracy from a knowledge of the number and distribution of independent rainfalls which occur, and the assumption of a drained surface so that each rainfall produces the same thickness of water film on the surface, and therefore, the same quantity of evaporational heat loss from the surface.

The principal heat flux whose calculation appeared to be in an unsatisfactory state, was that of the sensible heat transferred to or from the air. Since the air temperature is known, and the computer, if correctly programmed, will supply the ground-surface temperature, it remains to determine from the given meteorological data a value of heat transfer coefficient which can be set or varied on the apparatus, so that, operating between a programmed simulated air temperature and the demonstrated simulated surface temperature, it will serve to meter the correct flow of heat in either direction, depending on the temperature gradient, between the air and the ground surface. An estimation of the surface transfer coefficient can be obtained in the following manner.

Choice of equation for momentum diffusivity coefficient—The flux or diffusion of a property such as momentum, heat, or vapor across a horizontal plane in the atmosphere is usually expressed by the equation

$$q = C\rho K \partial p / \partial z \qquad (1)$$

where q = flux of property
C = constant depending on property
ρ = density of air
K = vertical eddy diffusion coefficient of property (a subscript m, h, v, to K will be used to denote a mass, heat, and vapor-eddy diffusivity, respectively)
p = concentration of property in air
z = height

and the evaluation of q depends on the determination of K. It becomes evident from an examination of the problem that the magnitude of K (which varies with height inversely as the vertical gradient of the property, since in the lower levels the flux of a property across horizontal planes at different heights is assumed equal) at a particular reference height depends on several factors. It is some measure of the turbulence of the atmosphere and is therefore a function of the temperature gradient or stability, and also of the wind velocity and the roughness of the surface. Taking into account these factors, many equations have been proposed to describe K and, after an examination of a number of them, three were chosen for further investigation with regard to field observations.

Some discussion has taken place in meteorological journals concerning the relationships existing between K_m, K_h, and K_v, and it is now generally assumed that K_m and K_v are equal, while K_m and K_h are not; this will be referred to again. Consequently the expressions chosen for comparison with experimental measurements involve K_m initially, and K_h will be considered further on.

The equations are

$$K_m = \frac{k_0^2 z_0 (z/z_0)^\beta u}{\ln (z/z_0)} \tag{2}$$

based on *Deacon's* [1949] work

$$K_m = \frac{k_0^2 (u_2 - u_1)(z_2 - z_1)}{[\ln (z_2/z_1)]^2} \tag{3}$$

from *Holzman's* [1943] evaporation equation,

where k_0 = von Karman's constant, = 0.40 usually
z_0 = a surface roughness indication
u = wind velocity at some reference height
β = exponent, indicative of atmospheric stability

The third method examined utilized the Bowen ratio, obtained from *University of Wisconsin* [1954] presentations of data measured during the Great Plains Turbulence Project. All the equations imply so-called 'rough surface' flow in which the roughnesses protrude through the laminar sublayer.

Occasions on which reliable observations were made, suitable for the testing of the chosen equations, are not common, and the most convenient are the *University of California's* [1954] measurements of wind shear force at the ground surface, also during the Great Plains Turbulence Project.

Shear on a horizontal plane in the atmosphere is manifested by mass transfer of air through the plane and consequently the shear stress can be calculated from the expression

$$\tau = \rho K_m \partial u / \partial z \tag{4}$$

where τ = shear stress. Consequently from a knowledge of wind velocity conditions prevailing at the site, it is possible to calculate the surface shear stress. Figure 1 shows a plot of τ_0 versus the wind velocity at a height of two meters on August 18–19, 1953, in which the calculated data are compared with those observed. Since the calculations were based on the hourly averages of wind velocities given in the Great Plains Project report issued by the *Johns Hopkins University* [1954] and the measured shear stresses were obtained during a fifteen-minute period only, during the pertinent hour, it was felt undesirable to present statistical comparison of the data. The *University of California* [1954] report contains a plot of the measurements.

In order to compute the shearing stress during one period from the wind velocities at different heights using (2), it is necessary to determine first z_0 and then β in (2) so that a value of K_m can be found at a particular height. Then, using this value of K_m, (4) will give the shearing stress. The roughness z_0 in this example was computed, after the method described by *Deacon* [1949], from the ratio of the wind velocities at 80 cm and 40 cm during neutral equilibrium conditions, when the logarithmic law of wind velocity distribution holds. The value of z_0 so obtained was assumed to hold throughout the period under consideration. At any time when the atmosphere is unstable or stable, Deacon's equation can be fitted to the velocity profile, using velocities at the same heights as before. Such a fitting yields a value of β for the period, applicable to the height range considered. The determination of K_m from (3) is less involved and needs no description.

It is not proposed to discuss the reasons for the discrepancies here, but it will be noticed that the use of (2) results in a very good agreement with the observed data. Although this agreement is

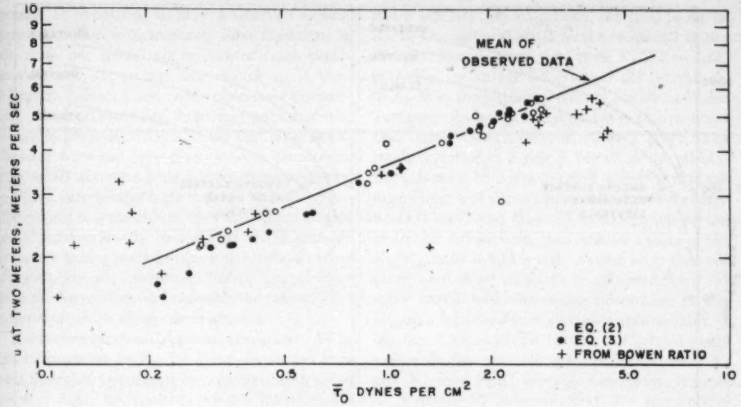

FIG. 1 – Wind velocity at two meters height versus surface shearing stress, calculated and observed for August 18–19, 1953, Great Plains Turbulence Project

demonstrated by calculations covering a short period of time only, the correlation was felt to be promising enough to warrant the preparation of charts (Fig. 2) for determining K_m. Since it was necessary to associate K_m with a particular height, a convenient reference level of 60 cm was chosen, which was the level at which K_m was calculated in the examples based on meteorological information at the 40- and 80-cm levels.

Some explanation of Figure 2 is required. The exponent β in (2) has been described as indicating the stability of the atmosphere at the height under consideration. Since temperature gradients can change the state of the air from stable to highly unstable, it was felt necessary (particularly in view of the areas of the ground surface to which this information was to apply) to consider only a representative moderate stability, a moderate instability, and a neutral equilibrium condition. These are given by β values of 0.88, 1.08, and 1.0, respectively, corresponding to Richardson's numbers of +0.06, −0.04, and 0. Such a course is further justified by reason of the unlikelihood of ever being able to calculate the value of the stability at any location. It will usually only be known that it was daytime and, therefore, unstable atmospheric conditions probably existed, or that it was night, and stability prevailed. Further approximations must be made when average values over weekly or monthly periods are required. Because of the large variation which K_m can undergo, it has been plotted on a logarithmic scale.

Since at low wind velocities, where smooth surfaces are concerned, it may be possible to obtain 'smooth surface' flow, which does not involve the roughness of the surface, a curve has also been drawn on Figure 2 which is obtained from the equation [*von Karman*, 1934]

$$u/u_* = 5.5 + 5.75 \log_{10} (u_* z/\nu) \qquad (5)$$

where $u_* = (\tau_0/\rho)^{\frac{1}{2}}$, the friction velocity, and ν = kinematic viscosity.

This expression holds only for adiabatic or neutral equilibrium conditions, as it contains no stability term. Reported observations [*Johns Hopkins University*, 1952] were investigated to see if smooth surface flow did actually occur in nature, but it was found that even wind velocities as low as 100 cm/sec over a surface of roughness $z_0 = 0.017$ cm were still in a transitional range between smooth and rough surface flow.

When no wind at all exists, and the conditions are stable, then a lower boundary of the momentum diffusivity coefficient is reached, and the value of molecular diffusivity, equal to 0.15 cm²/sec, is used. Conditions during which property transfer by molecular processes takes place may occur during a calm clear night, in which long-wave outgoing radiation cools off the ground surface and causes the build-up of a stable air layer next to the

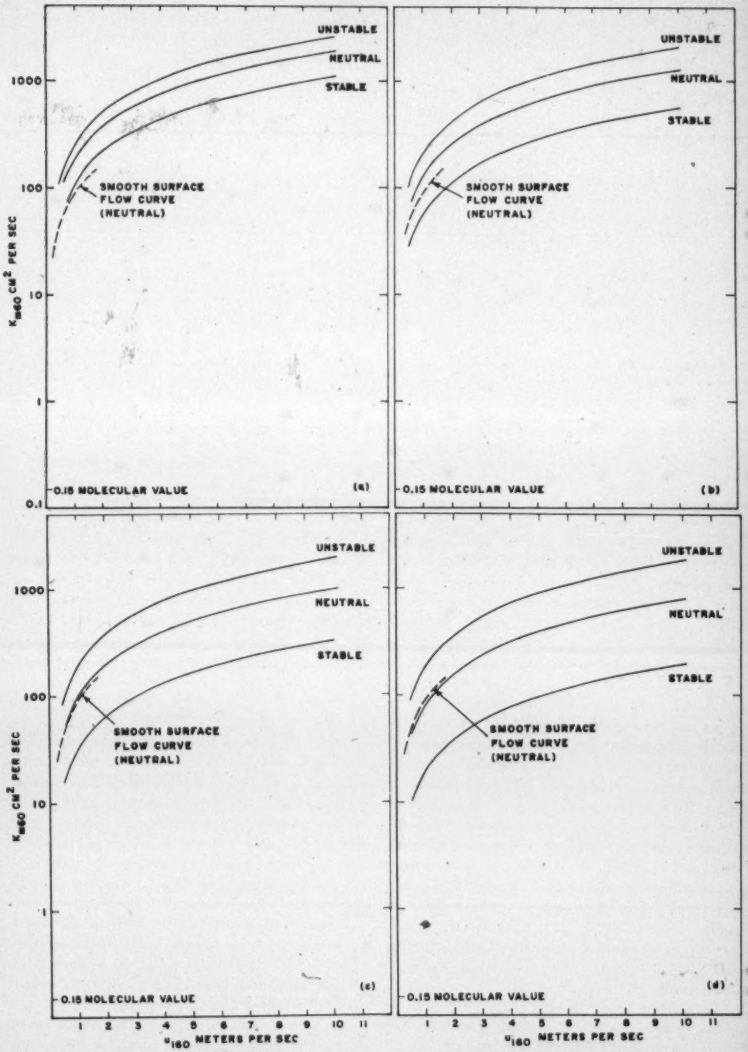

FIG. 2 – Momentum eddy diffusion coefficient versus wind velocity at 160 cm height for different stabilities and surface roughnesses (a) 1.0 cm; (b) 0.1 cm; (c) 0.01 cm; (d) 0.001 cm

ground. It is possible to have a situation arising during the day, with incoming solar radiation, in which no net lateral air movement takes place. In this case, convection cells, which are a very delicately balanced and rarely observed phenomenon, develop. However, from one published observation [*Bryson*, 1955] it seems that large sensible heat flows can take place in such conditions, with small accompanying temperature gradients, so that a surprisingly large value of 'diffusivity coefficient,' if it is possible to view the results on this basis, must evidently be assigned to the transfer processes taking place in convection cells. Further observations are necessary before quantitative data can be plotted, and care must be taken in the interpretation of these circumstances.

Estimation of thermal diffusivity coefficient—With the information on K_m for given conditions it is next desirable to estimate the corresponding value for K_h. Since the research for this investigation was carried out, the author has obtained the *Johns Hopkins University* [1954] Final Report on the Great Plains Turbulence Project in which work by M. H. Halstead indicates that at any small height, under any stability conditions, the ratio of K_h to K_m is constant and equal to the reciprocal of the Prandtl number. From this, then, $K_h/K_m = 1.41$. However, the author did evaluate the ratio of K_h to K_m from the published data of the Great Plains Turbulent Project, and has added to this information certain observations of *Pasquill* [1949]. The result is plotted in Figure 3, for which the calculations, it must be borne in mind, assumed that the momentum and vapor eddy coefficients were identical. If they were taken to be in relation to the molecular diffusivities, then smaller values of the K_h/K_m ratio would result. At the time this was carried out first, although it appeared that the ratio varied with increasing instability, it was assumed for calculation purposes that a value of between 1.5 and 2.0 for the K_h to K_m ratio would suffice during unstable conditions and that K_h and K_m were equal in stable conditions. It must be emphasized, however, that the temperature gradients and resulting heat flows on which the calculation of K_h/K_m was based during stable conditions were very small indeed, and that the assumption of a rational value such as 1.41 above would

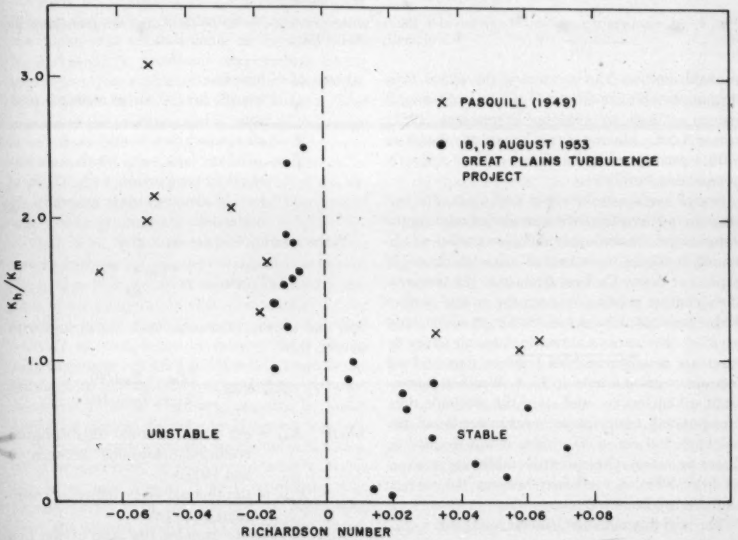

FIG. 3 – Ratio of thermal eddy diffusion coefficient to momentum eddy diffusion coefficient versus Richardson number

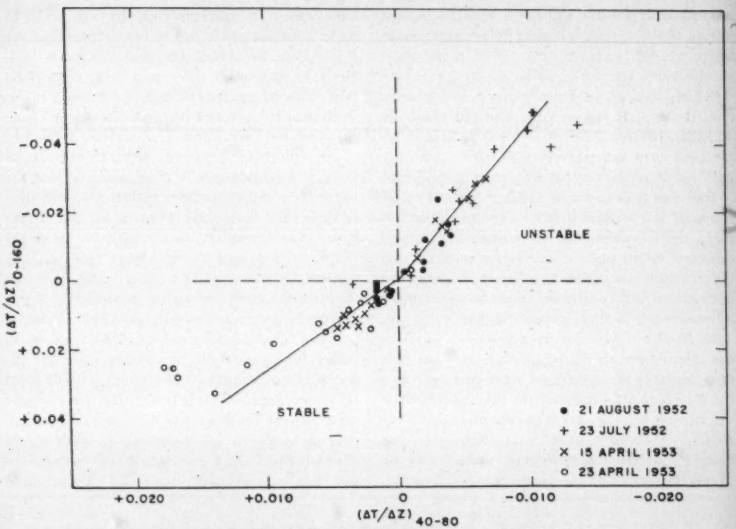

FIG. 4 – Air temperature gradient over interval 0–160 cm versus gradient over 40–80 cm; data from Johns Hopkins University [1952, 1953]

probably suffice. The question of the actual ratio during unstable conditions is still an open one, it seems, as data reported by *Vehrencamp* [1951], where K_h/K_m is given versus hour of the day, give values corresponding to Figure 3 for evidently comparable stabilities.

Overall surface heat-transfer coefficient—The last stage in the investigations consisted of relating the value of the thermal eddy diffusion coefficient obtained at 60 cm to an overall value which would express or define the heat flux across the temperature gradient existing between the ground surface and a convenient height in the air, at which temperature observations are made. Since air temperatures are usually recorded between four and six feet above ground level in U. S. Weather Bureau standard enclosures, and since the available data incorporated temperature measurements at the height of 160 cm or 63 inches, it was decided to direct the calculations toward establishing an overall heat diffusion coefficient between the surface and this height of 160 cm.

The heat flux equation, similar to (1) is

$$q_h = c_p \rho K_h (\partial T/\partial z + \Gamma) \qquad (1a)$$

where q_h = heat flux
c_p = specific heat of air at constant pressure
T = air temperature
Γ = adiabatic lapse rate, which is usually small in comparison with $\partial T/\partial z$ at low levels and may generally be neglected.

If the assumptions are made that

$$(\partial T/\partial z)_{60\,\mathrm{cm}} = \frac{(T_{40} - T_{80})}{40}$$

and that the flux of sensible heat is invariant with height, then

$$K_{h1}/K_{h60} = \frac{(T_{40} - T_{80})/40}{(T_0 - T_{160})/160} \qquad (6)$$

where K_{h1} = the overall thermal eddy diffusion coefficient obtaining between 0 and 160 cm
K_{h60} = the thermal eddy diffusion coefficient at 60 cm

Now, in order to examine the ratio of the two diffusivities empirically, it is necessary to utilize

data containing the surface temperature of the soil. Such surface temperatures are very difficult to measure, and only a few reports incorporate them, and then only on rare occasions. It is, of course, possible to estimate surface temperature fluctuations from calculations based on observed soil temperatures, but due to the unknown and very variable soil properties in the layers near the surface, these estimations are usually unreliable. The *Johns Hopkins University* [1952, 1953] reports contain surface temperatures which are considered reliable, measured on a few days, and these data have been used to plot $(\Delta T/\Delta z)_{40\text{-}80}$ versus $(\Delta T/\Delta z)_{0\text{-}160}$ in Figure 4. Again it may be stated that a straight line is not expected to describe the curve in general, adequately, but for moderate stabilities and instabilities it is found that the following values may be used

$$\left.\begin{array}{l}\text{Stable conditions}\\ \qquad K_{ht}/K_{h60} = 0.38\\ \text{Unstable conditions}\\ \qquad K_{ht}/K_{h60} = 0.22\end{array}\right\} \tag{7}$$

Since the K_{ht} value includes the effect of heat flux through the laminar boundary layer and sublayer, the thickness of which depends on the wind velocity and stability, non-linear relations may be expected at higher stability or instability conditions. Some theoretical work has been done on these aspects of the problem, and it is hoped to present it at a later date.

Summary of approach—All the necessary material has been supplied for the calculation of the air-ground heat transfer coefficient, and the method will now be summarized.

First of all, if it is desired to plot and use the hourly variation of transfer coefficient over several days, then it is presumed that at least hourly records of air temperature and wind velocity at the specified height exist. In many cases, the wind velocity at much higher elevations (say 30–50 ft) may have been recorded and it will be necessary to extrapolate this by either a logarithmic or power wind law, some of which are suggested by *Sutton* [1953], to obtain the velocity at about five feet.

With a knowledge of the roughness of the area, or more precisely, of the upwind surface, which can be estimated from Table 1, reproduced from *Deacon* [1949] with the addition of information from the present analysis, the appropriate section of Figure 2 can be entered to obtain values of K_{m60} based on guessed stability conditions.

TABLE 1 – *Table of roughness parameter, z_0 for typical surfaces*

z_0	Surface
cm	
10	Turnip field
1	Grass airports; prairie surface, O'Neill, Nebraska
0.1	Baseball field, spinach field, growth 5–6 mm, Seabrook, New Jersey, September 5, 1952
0.01	Bare rolled soil surface, Seabrook, New Jersey, August 21, 1952
0.001	Probably smooth ice surface

At this point the momentum diffusion coefficient, assumed equal to the vapor diffusivity, used in conjunction with the known vapor pressure gradient at 60 cm will give a value for the amount of evaporation taking place. The values of momentum eddy diffusion coefficient are then multiplied by a factor (probably the constant 1.41) according to Figure 3 to give K_{h60} which is then modified according to (7) from the stability prevailing. Since a surface transfer coefficient is usually defined by

$$q_h = S(T_2 - T_1) \tag{8}$$

it follows that here

$$S = \frac{c_p \rho K_{ht}}{160} \tag{9}$$

and values of $(c_p\rho)$ can be obtained from a knowledge of the air temperature to yield the required S.

However, if it is desired to calculate the surface coefficient over a period of several months or even a year, then average values must be resorted to. As this problem is of interest to studies of freezing and thawing cycles in the ground, some attention was devoted to it, when it appeared that an adequate representation could be obtained by neglecting the night-time transfer of sensible heat between the air and the ground.

It is not proposed to give much space here to this discussion, but it may be said that the ground, in general, loses heat to the air by day both by convection and by radiation, while at night the principal loss of heat is by long-wave outgoing radiation. Therefore in order to simulate a whole day's convective heat flow from the ground to the air, it is generally sufficiently accurate to take into account daylight conditions only. In other words, the amount of heat transferred to the air by convection in one day can be obtained by programming the computer with the average daytime air temperature, and a surface transfer coefficient based on the average daytime wind velocity and

reduced in the proportion of the daylight hours in the twenty-four over the period considered. This will give approximately correct amounts of heat flow to the air over the period considered, which is the factor of most interest to freezing and thawing depths prediction.

Conclusion—A step-by-step procedure, based on largely empirical findings, has been presented for the calculation of a surface transfer coefficient between the ground and a reference height in the air, when only commonly measured, and relatively easily obtainable meteorological data are present. This information will be supplied to a computing machine which will in turn yield the surface temperature to account for the necessary sensible heat transfer between the ground and the air.

It is not necessary to emphasize the crudeness of many of the assumptions on which the charts and plots are based, but they provide a method, taking into account all the pertinent meteorological factors, for estimating a necessary quantity more closely than has hitherto been possible. With more information on micrometeorological tests which are at present being carried out, and especially with more measurements in arctic conditions (the stability of the air in the months' long arctic night is a matter of conjecture) it is hoped to be able to refine and modify the charts to be of greater accuracy, if at all possible, and usefulness.

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A Nomogram for Log-Normal Frequency Analysis

L. L. WEISS

Abstract—A nomogram is presented for determining log-normal return period amounts directly from the mean and standard deviation of the annual-maximum series values. The return-period amounts as computed on the basis of a log-normal analysis are compared with those from a Gumbel analysis in the form of ratios as a function of the coefficient of variation of the annual-maximum series amounts.

Introduction—The logarithmic-normal probability law is widely used to describe the distribution of annual-maximum values of hourly or daily precipitation, flood flows, etc. This law provides an objective method for estimating the magnitudes of the events for particular return periods, or the probability of occurrence of events of a given size. Others make use of the Fisher-Tippett type-I distribution (sometimes called a Gumbel distribution) for the same purpose.

This paper presents some relations between the statistics of the two methods and provides a nomogram for rapid determination of the log-normal values for various return periods (or probabilities) directly from the values of the mean and standard deviation of the annual-maximum series data, without the necessity to use a table of logarithms or to make computations involving logarithms.

Nomogram for log-normal method—The normal law of error is given by

$$\varphi(x) = (1/\sigma\sqrt{2\pi}) \exp\left[-\tfrac{1}{2}\left(\frac{x-\bar{x}}{\sigma}\right)^2\right] \quad (1)$$

In the log-normal distribution, the natural logarithm of the variate replaces x in (1), that is

$$\varphi(y) = (1/\sigma_y\sqrt{2\pi}) \exp\left[-\tfrac{1}{2}\left(\frac{y-\bar{y}}{\sigma_y}\right)^2\right] \quad (2)$$

where $y = \ln X$, $\bar{y}$ is the mean, and σ_y the standard deviation of the natural logarithms of the variate X. From this, following *Kalinske* [1946], we have

$$\bar{X} = \int_{-\infty}^{\infty} X\varphi(y)\,dy \quad (3)$$

$$S_X^2 = \int_{-\infty}^{\infty} (X - \bar{X})^2\varphi(y)\,dy \quad (4)$$

Eq. (3) and (4) integrate to

$$\bar{X} = \exp(\bar{y} + \tfrac{1}{2}\sigma_y^2) \quad (5)$$

and

$$S_X = \bar{X}\,(\exp\sigma_y^2 - 1)^{\frac{1}{2}} \quad (6)$$

where $\bar{X}$ and S_X are the mean and standard deviation of the variate X, that is, the annual-maximum series values.

Eq. (5) and (6) can be rewritten, after transformation to common logarithms, as follows

$$\log \bar{X} = \bar{X}_L + 1.15129 S_{X_L}^2 \quad (7)$$

$$\log [C_v^2 + 1] = 2.3026 S_{X_L}^2 \quad (8)$$

where $\bar{X}_L$ and S_{X_L} are the mean and standard deviation of the common logarithms of the annual-maximum series values, and C_v is the coefficient of variation of the original variables (that is, the standard deviation divided by the mean).

The values of t (the number of standard units from the mean) corresponding to particular probabilities P, or return periods T, may be taken from tables of the integral of the normal curve, and selected values are given in Table 1. The value of log X corresponding to any probability will then be equal to the mean plus the appropriate value of t times the value of S_{X_L}. The value of the original variate for the given return period or probability is then

$$X_T = \log^{-1}[S_{X_L} t + \bar{X}_L] \quad (9)$$

The ratio of various log-normal return-period values to that for two years is readily expressed as

TABLE 1 – *Standard units from the mean for particular values of probability or return periods*

T	500	100	50	25	10	5	2
P	0.002	0.01	0.02	0.04	0.10	0.20	0.50
t	2.878	2.326	2.054	1.751	1.282	0.842	0

TABLE 2 – *Return-period ratios as functions of* C_v

500/2	$\log^{-1}\{1.8966\,[\log(C_v^2+1)]^{\frac{1}{2}}\}$
100/2	$\log^{-1}\{1.5328\,[\log(C_v^2+1)]^{\frac{1}{2}}\}$
50/2	$\log^{-1}\{1.3536\,[\log(C_v^2+1)]^{\frac{1}{2}}\}$
25/2	$\log^{-1}\{1.1539\,[\log(C_v^2+1)]^{\frac{1}{2}}\}$
10/2	$\log^{-1}\{0.8448\,[\log(C_v^2+1)]^{\frac{1}{2}}\}$
5/2	$\log^{-1}\{0.5549\,[\log(C_v^2+1)]^{\frac{1}{2}}\}$

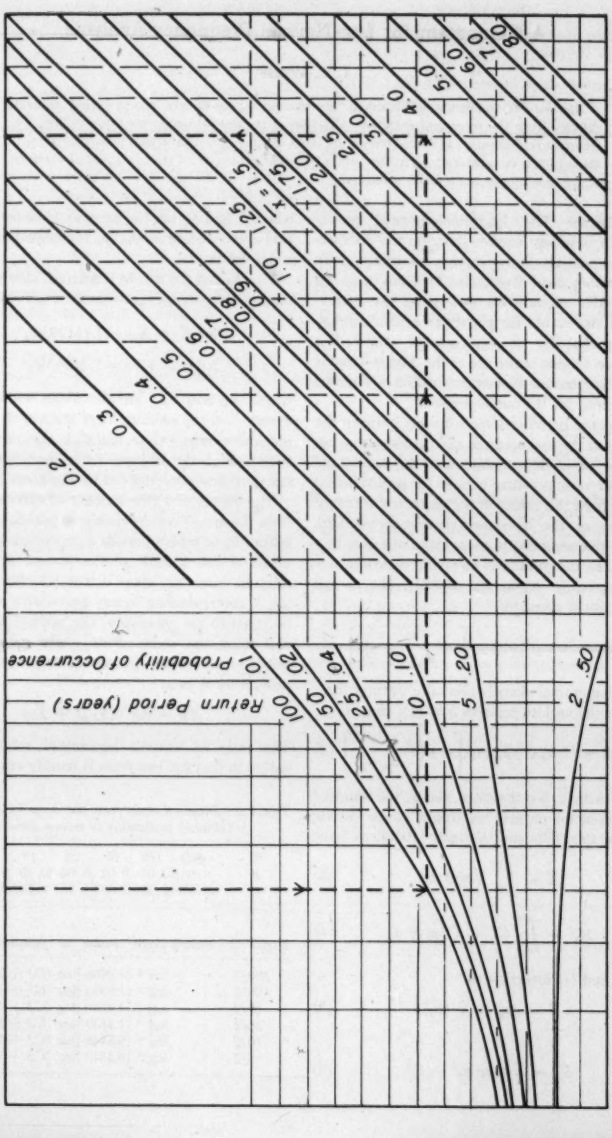

FIG. 1 – Nomogram for determining the log-normal distribution return-period amounts from the coefficient of variation $C_v = S_X/\overline{X}$, and the mean $\overline{X}$ of the annual-maximum (or extreme values) series; the $\overline{X}$ and X_L scales are relative; for example, for $\overline{X}$ = 20.0 use the 2.0 line and multiply the X_L value read by ten

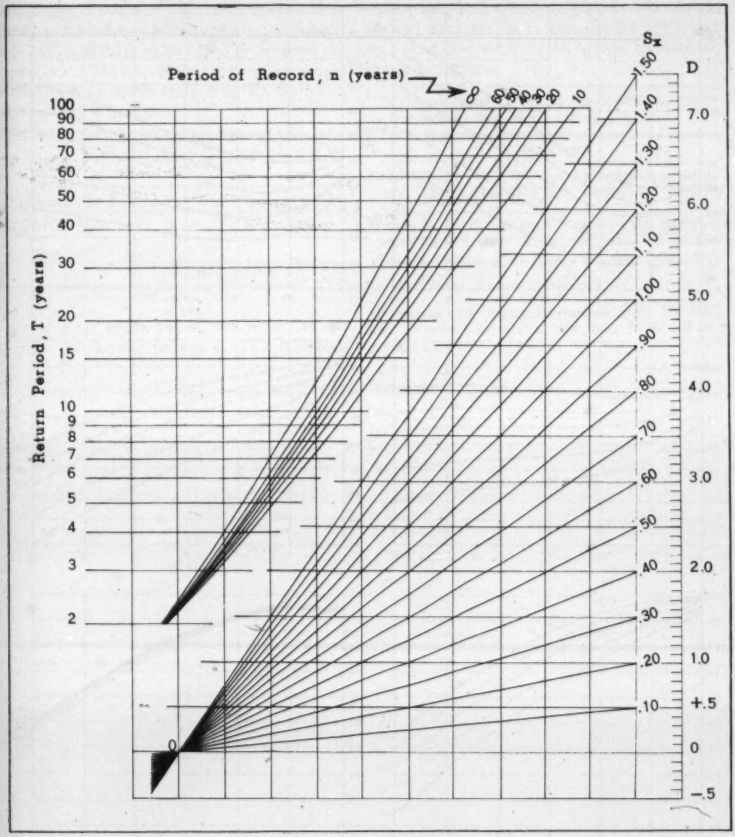

FIG. 2 – Nomogram to determine D, the amount to be added to the mean of the annual-maximum or extreme values series to get the Gumbel distribution value for any return period T; the S_X and D scales are relative; for example, for $S_X = 4.00$ use the line labeled 0.40 and multiply the D value obtained by ten

a function of C_v. Ratios of particular interest are given in Table 2.

The relations given in (7), (8), and (9) can be put in graphical form as shown in Figure 1. This nomogram permits the rapid determination of the log-normal amounts for various return periods, or probabilities, directly from the mean and standard deviation of the annual-maximum series values.

Use of the nomogram—Given the values of $\bar{X}$ and S_X for the annual-maximum as series 3.48 and 0.88, respectively. Required to find the log-normal amount for the 100-year return period (that is, the value with an occurrence probability of 0.01).

Determine $C_v = 0.88/3.48 = 0.25$

Enter the nomogram with $C_v = 0.25$ and move downward to the 100-year return-period line (that is, the 0.01 probability line), thence horizontally to the right to the line of $\bar{X} = 3.48$, thence upward to the amount on the horizontal scale at the top. The 100-year return-period log-normal

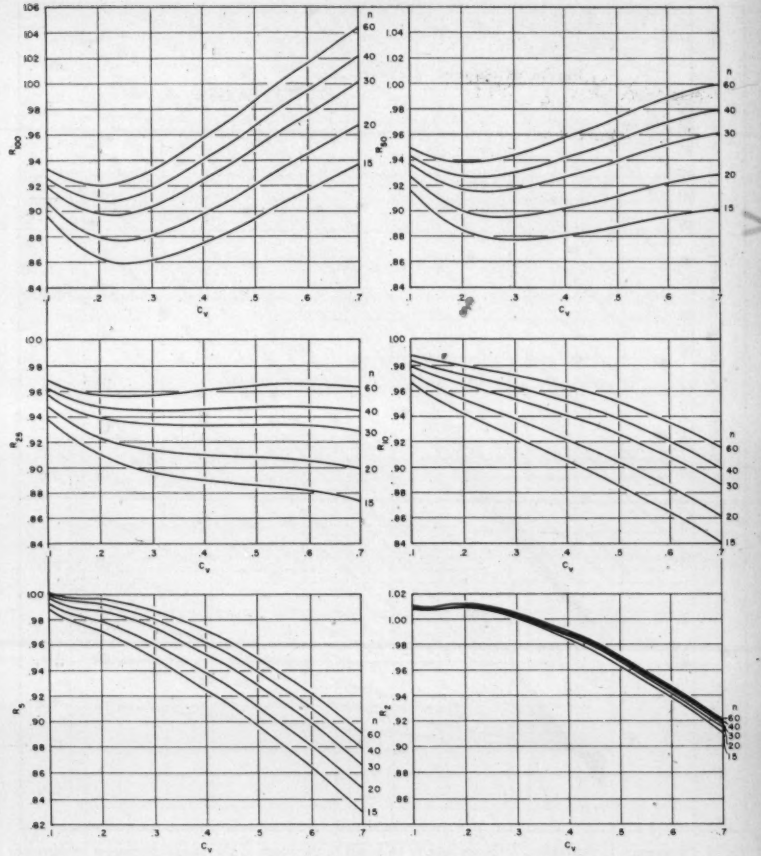

FIG. 3 – Ratio of the return-period values as computed by log-normal to those computed by the Gumbel method for selected return periods

amount is found to be 6.00. The dashed lines of the diagram illustrate the example.

Comparison of the two methods—The ratio of the return-period amounts as computed by the two methods can be illustrated as follows: The return-period values for log-normal analysis are given by (9). The return-period values given by the Fisher-Tippett type-I analysis (Gumbel method) are given by

$$X_{T_G} = S_X K + \bar{X} \qquad (10)$$

where K (a function of T and the number of years of record n in the annual series) is given in Table 3 of *Weiss* [1955]. A nomogram for use in Gumbel analysis [*Weiss*, 1955] is reproduced here as Figure 2. (Example: Given the mean value of 3.0 and standard deviation of 0.50 for the series of 40 extremes, required to determine the value that will be equalled or exceeded on the average once in 10 years (that is, will have a return period of 10 years). Enter left of diagram at $T = 10$, move

horizontally to line $n = 40$, thence downward to line $S_x = 0.50$, thence horizontally to the right to scale D to read 0.75, which added to 3.0 gives the answer, 3.75.) The ratio of the log-normal amounts to that for the Gumbel analysis for the particular return period T is then

$$R_T = \frac{X_T}{X_{TG}} = \frac{\log^{-1}[S_{X_L} t + \bar{X}_L]}{S_X K + \bar{X}} \qquad (11)$$

Substituting for $\bar{X}_L$ and S_{X_L} from (7) and (8), this can be rewritten

$$R_T = \frac{\log^{-1}[0.659t\{\log (C_v^2 + 1)\}^{\frac{1}{2}} - 0.5 \log (C_v^2 + 1)]}{KC_v + 1} \qquad (12)$$

For a given return period, the ratio given in equation (12) depends only on C_v and n. The ratio values computed for return periods 2, 5, 10, 25, 50, and 100 years for C_v values of 0.1 to 0.7, and for values of n of 15, 20, 30, 40, and 60 years are shown in Figure 3.

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Laboratory Investigation of Some Characteristics of the Eppley Pyrheliometer*

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Abstract—The pyranometer of Eppley shows the following deviations of its scale value:

(1) The temperature coefficient consists of coefficients of the thermopile and of the different heat exchange parameters.

(2) Air convection within the glass bulb causes a dependency of the scale value on the angle between the receiving surface and the direction of gravity.

(3) Rays from below the instrument plane may be reflected by the glass ball onto the receiving surface.

(4) The existing black paint has a specular reflection which causes a dependency on the angle of incidence. All deviations can be brought under control by suitable modification or calibration.

The Eppley pyrheliometer measures on a flat surface hemispherical radiation of wavelengths less than three microns. Textbooks on meteorological radiation instruments, *Kleinschmidt* [1935], *Mörikofer* [1939], and *Buettner* and *Albrecht* [1929], and *Albrecht* and *Buettner* [1930] classify the Eppley as a pyranometer; however, the term Eppley pyrheliometer will be used in this report.

Each Eppley pyrheliometer is individually calibrated for operation in a horizontal position to measure radiation from the hemisphere above the horizon. In recent years an increasing number of investigators have used the Eppley to measure radiation reflected from various surfaces, radiation falling on vertical walls, etc. These applications require that the instrument be mounted in a position other than that for which it was calibrated. The purpose of the present investigation is to find the magnitude of some of the errors in the Eppley under different conditions of mounting and exposure and to present suggestions which might improve the accuracy of such radiation measurements. The computed percentage errors and correction factors are presented only to illustrate the probable magnitude of errors which might be encountered. The great differences between individual instruments and mounting procedures indicate that correction factors for a given set of data and for each Eppley can be arrived at only by extensive testing of the instrument and installation. In some instances only one or two of the types of errors may be significant.

The Eppley resembles the thermoelectric pyranometer originally constructed for the U. S. Weather Bureau by *Kimball* and *Hobbs* [1923]. Its sensing element consists of either a 10- or a 50-junction thermopile of gold-paladium and platinum-rhodium alloys connecting two thermally-insulated equi-area, annular, copper rings mounted concentrically on a common plane. The outer ring is coated with magnesium oxide and the inner ring brush-painted with soot mixed with a shellac binder. The thermopile assembly is horizontally mounted in the center of a clear, spherical, soda-lime glass bulb whose diameter is about three times that of the outer ring. A convenient tripod base is equipped with leveling screws and a spirit level.

Miller [1942] reports that the magnesium oxide surface has a reflectivity of 97 to 98 pct for radiation in the solar wavelengths but is a good absorber of long-wave radiation. The blackened surface is highly absorbent in both the long and short wavelengths. Near equal absorption of long-wave radiation by the two plates minimizes the effect of radiation from the glass cover. The result is a thermal difference between the rings producing a thermoelectric EMF across the thermopile, which is approximately proportional to radiation of wavelengths between 0.3 and 3 μ.

The temperature coefficient—It has been shown by *MacDonald* [1951] that the thermopile voltage output for constant radiation decreases with increase in ambient temperature. The average measured temperature coefficient of the scale value (cal cm^{-2} min^{-1} per scale unit) for seven Eppleys was $\kappa = +0.085$ %/° per °C. The instrument temperature ranged from −40 to +48.9°C. Individual instruments showed κ data between −0.041 and −0.127. *Courvoisier* [1951] reports +0.065 for one Eppley for temperatures between +17 to +57°C. These data refer to voltage output ratios and not to currents in any current drawing circuit. The observed values are large enough to

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cause serious errors if variation of output with temperature is neglected.

Buettner and *Albrecht* [1929] and *Albrecht* and *Buettner* [1930] have shown that the temperature coefficient may be expressed by

$$\kappa = \frac{\Delta(Q/V)}{Q/V} = \frac{\Delta h_c + \Delta h_v + \Delta h_m + \Delta h_r}{h_c + h_v + h_m + h_r} + \frac{\Delta\gamma}{\gamma} \quad (1)$$

where Δ indicates change per 1°C temperature increase; Q is the absorbed radiation; h_c, h_v, h_m, and h_r, the heat transfer coefficient by conduction, convection, solid contact, and radiation; $\gamma = \Delta T/V$ where ΔT is the temperature difference of black and white ring; and V is the potentiometer reading. The value of Δh_m is small since solids change their conductivity with temperature much less than air. The value of h_m is, of course, unknown but probably not negligible, but h_r and therefore Δh_r may be neglected if infrared absorption and shape factor of black and white rings are equal. The separation of conduction and convection can safely be done, at least in this approach. Details on borderline cases of conductive and convective heat transfer are discussed elsewhere by *Buettner* [1955].

According to *MacDonald* [1951] the average values of κ and $\Delta\gamma/\gamma$ are, respectively, 0.00085 deg^{-1} and -0.0011 deg^{-1}. For conductive transfer $h_c \propto \lambda \propto T^{0.84}$ where λ represents conductivity of air. Around $T = 300^0K$ this requires that $\Delta h_c/h_c = +0.003$ deg^{-1}. The convective coefficient, $\Delta h_v/h_v$, is expected to depend on Grasshof's number and λ, namely

$$h_v \propto \lambda \left(\frac{d^3 g \rho^2 \Delta T}{\mu^2 T}\right)^n \quad (2)$$

where d is a length; g, the acceleration of gravity; ρ the density; and μ the viscosity of air. Therefore (2) becomes for constant ρ and d

$$h_v \propto \lambda \mu^{-2n} T^{-n} \quad (3)$$

The temperature coefficients of conductivity and viscosity are about $\lambda \propto T^{0.84}$ and $\mu \propto T^{0.75}$. For free convection within small closed containers Buettner (paper in preparation) has shown that n is larger than 0.25, the figure usually found for free or thermal convection around heated bodies. Assuming $n = 1/3$, (3) becomes

$$h_v \propto T^{0.84} T^{-0.5} T^{-0.33} \approx T^0 \quad (4)$$

Consequently the temperature coefficient of the convective transfer, $\Delta h_v/h_v$, is assumed to be very small. Neglecting this, (1) may be written

$$\kappa = \frac{\Delta\gamma}{\gamma} + \frac{\Delta h_c/h_c}{1 + (h_v + h_m)/h_c} \text{ deg}^{-1} \quad (5)$$

Inserting data for κ, $\Delta\gamma/\gamma$, and $\Delta h_c/h_c$ we find

$$h_v + h_m = 0.58 h_c \quad (6)$$

Eq. (5) and (6) show that the temperature coefficient of the Eppley is decreased by convection. The signs of $\Delta\gamma/\gamma$ and $\Delta h_c/h_c$ are opposite; that is, the change of thermoelectric output partly cancels the effect of change of air conductivity with temperature. As (5) shows, increase in $h_v + h_m$ would decrease the temperature coefficient, and, of course, the sensitivity of the instrument, V/Q. Variations in h_v or h_m probably explain variations of the reported κ's for individual instruments.

Error from convection within the bulb—The Eppley pyrheliometer bulb is filled with desiccated air at normal temperature and pressure. In a gravitational field, heating of the thermopile surface should result in convective currents within the glass shell providing that the glass bulb is large enough to allow convection to take place. The convective currents must cool the warm surfaces more than the cooler ones, and convey heat directly from warm to cold surfaces with the net effect of reducing the thermopile EMF below what it would be in the absence of convection.

The following experiments were carried out to determine the effect of orientation of the instrument with respect to the gravitational field. The change in output of an Eppley exposed to constant radiation when the instrument was inverted was investigated in two ways. First, the Eppley was rigidly mounted to a vertical support facing a lamp, and a collimating lens was secured to the opposite end of the support. This frame, pivoted near the center around a horizontal axis, permitted the positions of the light and the Eppley to be quickly changed without interfering with their relative position or spacing. The output was recorded for

TABLE 1 – *Percentage change in output from the output in normal position with plates facing zenith*

Eppley no.	No. of junctions	Plates face horizon	Plates face nadir
		pct	pct
2146	50	−3.0	−5.5
2142	50	−2.2	−4.0
2096	50	−2.7	−3.3
2168	10	...	−4.0
Mean		−2.6	−5.4

the usual (horizontal), the inverted, and the vertical position of the plate. Results for four individual instruments are summarized in Table 1. The errors were found for source-intensity range of 0 to 0.5 cal cm^{-2} min^{-1}. The error increased slightly with increasing radiation. The second method tried excluded any variations in lamp intensity as the lamp position was changed. The Eppley was mounted on the vertical member and the light source on the horizontal member of a L-shaped frame. A plane mirror oriented about 45° from the horizontal member of the frame reflected the light to the thermopile surface. The relative positions of sensing element, mirror, and light source were rigidly fixed. The entire assembly could be inverted. The results obtained in this manner were consistent with those listed in Table 1.

The error appears to originate from changes in the convective pattern within the glass bulb. In the usual zenith-facing position, heating of the blackened ring causes convection. The warmed air is cooled by the glass wall of the bulb before, on returning, it passes over the whitened ring. When the receiving plate faces the horizon, the ascending currents first pass over a portion of the white ring, thus decreasing the temperature difference between the two rings. If the plates face the nadir, warm air passes outward over the entire white ring before ascending to the glass cover, resulting in an output even less than when the instrument faces the horizon (see Table 1).

These results are at some variance with those obtained by the Weather Bureau. *MacDonald* [1951] found a four or five per cent decrease in indicated radiation intensity with the receiver facing the horizon as compared with the usual zenith-facing position; but he found no significant difference when the instrument was facing the nadir.

Error from glass reflection—An Eppley facing the horizon or the nadir and not shielded from direct solar radiation from above the plane of the thermopile receiving surface can suffer an error in output due to reflection from the surface of the glass cover onto the receiving surface. A pyrheliometer facing the zenith but subject to reflected radiation from an ice or snow surface beneath would also be slightly affected.

In detail when a solar beam enters an Eppley from below the plane of the thermopile, a portion of the beam is cut off by the thermopile mount, the remaining continues on and strikes the surface of the glass cover on the opposite side; part of this radiation is reflected back toward the thermopile, the glass acting as a concave mirror. The result is a crescent-shaped pattern of reflected light striking

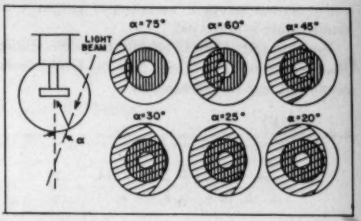

FIG. 1 – The portion of the receiving surface illuminated by radiation reflected from the inner glass surfaces

the thermopile surface (see Fig. 1). For zenith angles of the Sun from 90° to 60° the black and white rings are almost equally illuminated. This results in an increase in thermoelectric output. However, for zenith angles less than 60°, the white ring is illuminated more than the black ring. Even though the white surface is believed to have a reflectivity of 97 to 98 pct [*Miller*, 1942, comment by *Hand*] this leads to heating of the white ring compared to the black and thus to a reduced output from the thermopile.

Some of the radiation which enters the glass cover at a zenith angle α is reflected from the inner glass surface. The reflected radiation either adds to or subtracts from the indicated intensity depending on the sun angle. The unhatched area represents the illuminated portion; the hatched area a shaded portion of the disc.

An inverted Eppley was exposed to a collimated beam of light from zenith angles from 0° to 90°. The electrical output of the Eppley was found to change from plus to minus as the beam angle was altered. In order to estimate the magnitude of the error, the percentage of a collimated beam reflected to the receiving surface by the glass cover was measured for various zenith angles. Then the error shown in Fig. 2 was computed for various radiation intensities from below. The combination of reflection from the underlying surface and from the glass may lead to a large percentage error in albedo measurements, particularly if the underlying surface is a poor reflector (low albedo).

The magnitude of the glass reflection errors of the inverted Eppley will depend on the albedo, the method of mounting the instrument, and the shielding provided.

A cylindrical shield having the same height as the thermopile sensing surface could effectively eliminate glass reflections due to direct solar radiation. The shield should have a reflecting white

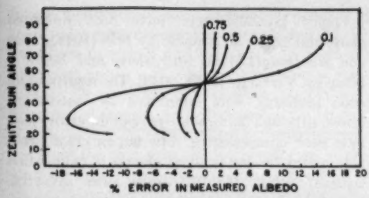

Fig. 2 – Per cent error contributed by glass reflection to measurement of light from reflecting surface below an inverted pyrheliometer; values on the four curves: true albedos of the reflecting surface

outer surface to minimize heating of the instrument and a blackened inner surface to minimize reflections. This cylinder could be designed to permit the free flow of air about the glass cover in order to prevent warm air from being trapped near the glass cover. Such shields, designed by I. F. Hand and A. H. Conover, have been in use on Eppleys facing north, east, south, and west horizons at the Blue Hill Meteorological Observatory for several years.

Errors from specular reflectivity of receiver plate— The response of the Eppley to light incident at angles smaller than 90° has been examined by *Woertz* and *Hand* [1941] and *MacDonald* [1951]. A perfect instrument should have no specular characteristics, that is, its receiving surfaces should follow Lambert's cosine law. A Bureau of Standards test of the specular response of two pyrheliometers, reported by *MacDonald* [1951], showed qualitatively similar response characteristics for all instruments, although there were large quantitative differences.

The specular response characteristics of five Eppleys and one Moll-Gorczynski were examined here to determine the differences between the individual units and also to compare these results with those previously reported by *Woertz* and *Hand* [1941] and *MacDonald* [1951]. Each instrument tested was mounted on a horizontal, graduated turntable so that the pyrheliometer plate faced the horizon and was centered at the center of the turntable. A parallel beam of light illuminated the plate. The receiving surface was aligned by an optical method accurate to within 0.3°.

A 1000-watt tungsten-filament projector lamp was used as a light source. The voltage applied to the bulb was stabilized with a carbon-pile regulator. It was estimated that with a one-mm glass filter this provided a tungsten emitter temperature of 2800°K. *MacDonald* and *Foster* [1954] have shown that only a very small error is introduced by using a tungsten spectrum instead of natural sunlight.

The experimental steps were as follows. Normal incident radiation intensity from the tungsten emitter was first measured. Then, indicated radiation intensities at various angles were measured alternately with the intensity at normal incidence. The per cent of normal incidence $x \cos \alpha$ was computed from

$$\beta = 100\ (I_i/I_n) \sec \alpha \qquad (7)$$

where α = zenith angle of the radiating source; I_i = radiation intensity at angle α measured by Eppley, and I_n = normal incidence radiation intensity, measured by Eppley. Results are given in Figure 3.

Woertz and *Hand* [1941] have suggested that the deviation from a true cosine response characteristic might be due to (a) sensing rings not mounted parallel, (b) irregularities in the black surface. *Miller* [1942] has suggested that (c) the dependence

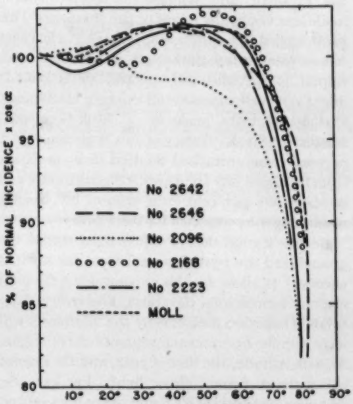

Fig. 3 – Deviation of five Eppleys and one Moll-Gorczynski from the cosine law for different zenith angles

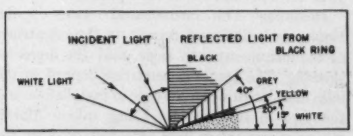

Fig. 4 – Visual observation of specular reflection from the blackened surface of an Eppley pyrheliometer

of the absorption of the lampblack on the angles of incidence might cause error. The latter appeared to be the major source of error in the experiments reported here, for visual observation of the blackened surface at various angles of incidence showed a highly specular reflectance (see Fig 4).

If the thermopile surface is illuminated by a beam from 15° above the plane of the surface, visual observation shows no difference in appearance between the white and black surfaces from 0° to 15° reflected angle, that is, both rings appear white. From 15° to 20° the blackened ring appears yellow. From 20° to 40° reflected angle, the surface appears grey. Above 40° the surface has a black appearance. This color phenomenon, of course, indicates a spectral effect within the specular error. A study was made of the characteristics of a black lacquer manufactured by Thos. Parsons and Sons in London and claimed to be superior to other paints in blackness. The Parsons black is used on the Beckman and Whitley radiometer. Checks made here verify the claims of the producers. This paint applied to a surface many times as a fine mist from a paint spray gun is very nearly black with respect to specular and spectral deviations. It might very well supersede all existing blackenings. Preliminary tests made on a Moll-Gorczynski solarimeter (by R. Hubley of this department in a personal communication) resulted in no deviation from the cosine law up to near 80° zenith angle and of about five per cent error around 80°. Similar results might be expected for the Eppley.

Because a good deal of diffuse light reaches the ground (and the pyrheliometer) from the sky it is necessary to allow for this in computing the total error for various solar elevations. The error in daily totals of radiation measured by the instrument will vary with the instrumental response curve (Figure 3), with latitude, the time of year, and the amount of scattered versus direct light. For example, assuming a latitude of 60°N and using the solar and sky brightness data from the Helsingfors (60°N, 25°E [*Hann-Süring* 1939, pp. 52, 67]) Instrument 2096 would give values six per cent too low in mid-June and 9 pct too low at the equinoxes.

Discussion—The instrumental errors in the Eppley pyrheliometers depend on the orientation of the instrument, sun angle, and the degree of shielding. The errors encountered depend on the individual instrument, the type of installation, and the type of observations being taken. Albedo measurements taken over bare soil or other absorbing material have a greater proportional error than those taken over ice or other reflecting material.

Eppley pyrheliometers have been mounted above and below an airplane by *Fritz* [1948], *Fritz* and *MacDonald* [1951] and above and below a blimp by *Neiburger* [1948, 1949]. The results in all cases probably were influenced by instrument errors, although during some periods the errors may have been compensating. The largest error probably would be due to some change in calibration constant when the instrument was inverted. Specular reflection would decrease the output from the instrument recording incoming solar radiation, particularly at low sun angles, but would have little effect on the diffuse radiation from below. Errors from glass reflections would depend on the individual installation. The instrument mountings used by the *Corps of Engineers* [1950, plate 2] (a proposed installation) and *Anderson* [1953] would experience, in addition to specular and gravity errors, a variation in instrument constant depending on the sun angle and the reflectivity of the surface being observed. Anderson, at the Lake Hefner installation, used two inverted pyrheliometers with opposite halves of glass cover blackened to cover a hemisphere below the horizon without receiving radiation from a supporting raft. It seems that blackening one half of the glass cover would so alter the equilibrium convective pattern within the bulb that a complete redetermination of the thermopile constants would be necessary.

Conclusions—When the Eppley pyrheliometer is used for albedo measurements, a number of instrumental errors must be taken into consideration. In most cases, correction factors can be determined for individual instruments to compensate for errors due to inverting the instrument, glass reflections, and the dependence of the absorptivity of the black ring on the angle of incidence. Better shielding at present instrument sites should eliminate the error caused by glass reflection.

The observed highly specular reflection from the absorbing ring indicates this property may be the major cause of the deviation from a true cosine response curve. Experiments indicate that the Eppley specular characteristics can be greatly improved by using a new paint.

In its present form (that is, present absorbing surface, single calibration constant, etc.), the Eppley pyrheliometer does not appear suitable for pyranometer measurements at high latitudes. For middle-latitude measurements, extensive calibration of the present units should considerably improve the accuracy of the instrument. Minor modifications of cover design and surface coatings could lead to a greatly improved instrument.

Summary—Laboratory investigations have con-

firmed field observations of inconsistent behavior of the Eppley pyranometer. Experiments and theories are given to explain and show ways to avoid the following errors: (1) variable temperature coefficient; (2) variation of thermopile output with direction of gravity, and effect caused by internal air convection; (3) errors caused by radiation coming from the back side and being reflected by the glass cover; (4) errors from specular reflectivity of the black receiver ring and the resulting deviation of response from the cosine law.

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Intensity and Frequency of Severe Storms in the Gulf of Alaska*

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Abstract—A review of the circumstances surrounding the sinking of the S.S. *Pennsylvania* with all hands in the Gulf of Alaska during January, 1952, necessitated an historical survey of severe storms in the Gulf of Alaska. The purpose of the investigation was (1) to determine from weather data the frequency and variability of occurrence of storms which would generate very high waves, and (2) to demonstrate the importance of factors other than measured wind speed such as duration, fetch, and air-sea temperature difference on development of very high wind waves. Criteria were developed for screening out the storms which probably generated high waves and sustained them for long durations. From the records for the winters of 1922–23 to 1951–52, excluding World War II years, 15 storms were selected and critically examined for their wave creating potential. The *Pennsylvania* storm of January 8–10, 1952, was considered the most severe and herein is compared with two other storms of higher wind speeds which did not generate higher waves. In addition, a longer-period storm survey of high January winds shows a large annual variability with January 1952 the extreme.

Introduction—The S. S. *Pennsylvania*, en route from Seattle to Yokohama, reported mountainous seas at 14 h 35 m (UT) on January 9, 1952. During the next ten hours damage was sustained which forced the 45 men aboard to abandon ship. The last message "Leaving now" was sent at 00 h 30 m, January 10, 1952. The Weather-Rescue Ship 4YP, about 250 mi to the west, was heading into the northwesterly wind and sea when it received the request for aid from the *Pennsylvania*. It was delayed in its rescue mission because the sea was too dangerous to negotiate the necessary turn to the east. The only evidence of the *Pennsylvania* which was found during the search for survivors was an overturned life boat.

For legal purposes, a storm survey was made to compare the *Pennsylvania* storm with the major storms occurring in the Gulf of Alaska from 45 N to 60 N and from 130 W to 170 W. The comparison was based on the potential of each storm to develop and to sustain high waves. Throughout this discussion the term wave height will refer to the significant wave height as defined by *Munk* and *Arthur* [1952]. The most extensive weather records available for this study were used. These were the historical weather maps for the northern hemisphere [*U. S. Weather Bureau*].

Selection of severe storms—Criteria for screening severe storms were developed for the historical weather maps. Criterion I was a geostrophic wind speed of 60 mph extending over a 10-degree fetch and appearing on two consecutive 24-hour charts, which would reasonably assure high intensity throughout a minimum of 24 hours. Storms meeting these basic requirements were eliminated if they were rapidly moving away from the waves they were generating. These storms were either moving with speeds in excess of 35 knots or their fetch was moving at an angle greater than 45° relative to the major axis of the storm.

Fifty-nine storms met or exceeded the conditions set up for Criterion I during the twenty-four winters (November–February) 1922–23 to 1938–39, and 1945–52 inclusive. Presumably all of these storms were capable of generating significant waves greater than 25 feet in height. Figure 1 shows the time distribution of these severe storms. The numbers in the circles are the storms occurring during each individual month for each winter. Notably, no storms were severe enough to meet the criteria for the period January, 1935, to November, 1938, inclusive. This was a relatively mild period. On the other hand, the winters of 1932–33 and 1951–52 were considerably more severe than the average.

Selection of very severe storms—The 59 storms selected by Criterion I were subjected to further screening on the basis of a second criterion. Criterion II consisted of a geostrophic wind of 80 mph for a fetch of five degrees on either of the two maps used in Criterion I. This reduced the number of storms to 15. Almost half of these storms occurred during the winters of 1932–33 and 1951–52. Months when these storms occurred are shown as black boxes around the circles on Figure 1. Each month shown had a single Criterion II storm, except for January, 1952, which had three Criterion II storms.

Wave records from the Weather Ship 4YP,

* Contribution No. 23, Department of Meteorology and Climatology, University of Washington. Contribution No. 3 in Oceanography and Limnology, Oregon State College. Contribution No. 203, Department of Oceanography, University of Washington.

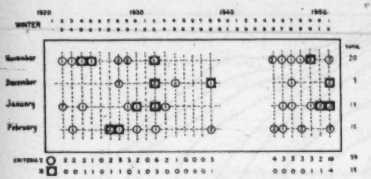

FIG. 1 – Occurrence of severe storms in the Gulf of Alaska which would have developed and sustained high surface waves

stationed in the Gulf of Alaska since 1949, offered a check on the effectiveness of the two criteria. Criterion I selected all storms which produced significant wave heights at 4YP of 25 ft or greater for a duration of nine or more hours, that is, four consecutive three-hourly reports of observed wave height. Part of the wave data were missing from one borderline storm which was not selected by Criterion I but may have had approximately nine hours of high waves at 4YP. Criterion II selected all storms which produced significant wave heights of 35 ft or greater for the same duration. They both failed to select individual storms with high waves of short duration (less than nine hours) because the 24-hour interval between maps placed a premium on long duration. On the other hand, two thirds of both Criterion I and Criterion II storms were accompanied by reported wave heights of 25 and 35 ft respectively at 4YP with durations of nine or more hours. For the other selected storms the waves approached these lower limits in height and duration, or the areas of maximum wave-height potential were some distance from the location of the Weather Ship 4YP. The original purpose, which was to select the storms with high waves with long durations of the order of 18 to 24 hours, was realized.

A running hindcast of significant wave height was then made for each of the 15 most severe storms which were selected on the basis of the two criteria. This was compared with the hindcast for the *Pennsylvania* storm for the position where the ship went down as well as the wave heights recorded at 4YP. In our opinion the *Pennsylvania* storm produced the highest waves for the longest period of time of any storm occurring during the 24-year period under consideration.

Statistical wave studies—An examination of the data presented in Figure 1 points up the difficulty in making statistical studies of wave conditions in these latitudes [*Burt* and *Saur*, 1948]. As an example *Harney*, *Saur*, and *Robinson* [1949] made a careful statistical study and compilation of wave conditions for four open sea locations in the North Pacific Ocean. One of their areas was approximately the center of the area considered in the present study. The latter study is based on the three-year period 1936–38. The weather maps for these years were the latest available in the historical series at the time their study was made (1946), and were considered the very best available. Figure 1 shows that this was the longest period of time with less than the normal amount of severe weather that could have been selected. During their winter (December–March) only one severe storm was selected by our Criterion I. Their data for the winter months show that waves greater than 20 ft in height may be expected only 2.2 pct of the time in the Gulf of Alaska. Our data, which are based on information which was not available at the time their study was made, shows that the 1951–52 winter period was about ten times as severe as their average from the standpoint of the frequency of waves greater than 20 ft in height. In 1951–52 the 2.2 pct frequency level would have been approximately 35 ft rather than 20 ft.

A second study of wave conditions utilized the Gulf of Alaska as the principal generating area for waves arriving at Cape Blanco and other points on the west coast of the United States. This study by *Saur* and others [1947] was again based on weather maps for the comparatively mild winters from 1936 to 1938. Decayed waves in excess of 20 ft were predicted only 0.2 pct of the time at Cape Blanco. The weather data for 1951–52 indicate that during occasional years the frequency of waves with heights in excess of 20 ft would probably be greater by a factor of ten than that which occurred during the comparatively mild winters of 1936–1938.

Description of the Pennsylvania *storm*—The storm moved across the Aleutian Islands on January 7, 1952. It intensified rapidly on January 8 as it moved southeastward into the Gulf of Alaska, then remained as a very intense storm in a quasi-stationary position during January 9. The position of the storm at 06 h 30 m (UT) on January 9 is shown on Figure 2. The stippled arrow on Figure 2 shows the trajectory of the very cold air that streamed southeastward toward 4YP resulting in air-sea temperature differences of minus 10 to 12°F. This current remained remarkably steady from mid-day on the 8th through the 9th. This means that waves formed along the Aleutian chain would continue to grow in height as they

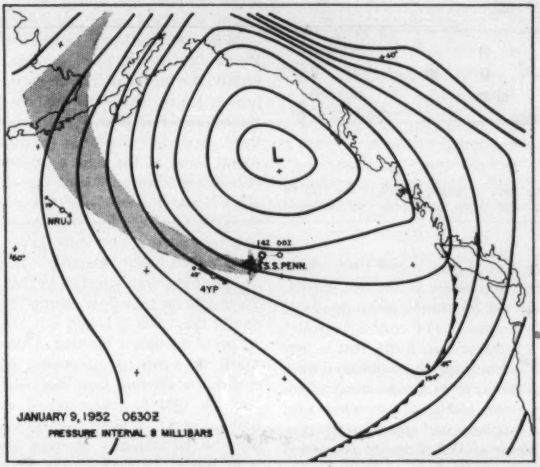

FIG. 2 – Surface weather map for the Gulf of Alaska, January 9, 1952, 06h30m (UT)

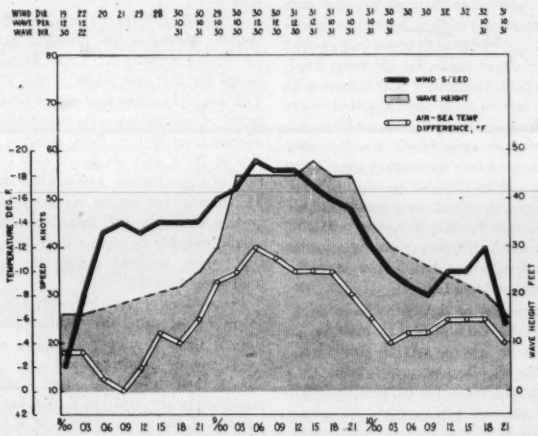

FIG. 3 – Meteorological and oceanographic data for the *Pennsylvania* storm of January 8–10, 1952 which were recorded at Weather Ship 4YP, 50° N, 145° W

approached 4YP and the position of the S.S. *Pennsylvania* since they were acted upon by winds of increasing speed and nearly constant direction. In Figure 2, the arrow at transient Weather Ship NRUJ indicates the direction of the recorded waves, 300° which had reached a height of 19 ft. Further downstream at 4YP the waves had the same direction but the height had increased to 45

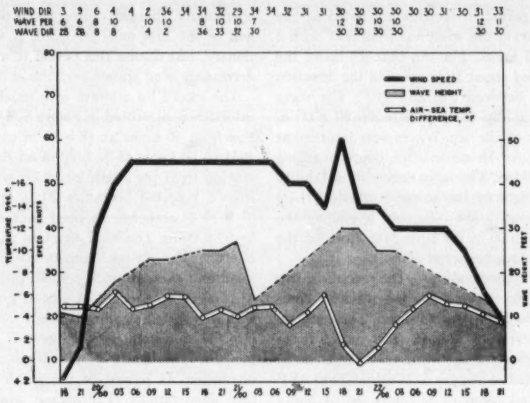

FIG. 4 – Meteorological and oceanographic data for the storm of January 19–22, 1951, recorded at 4YP

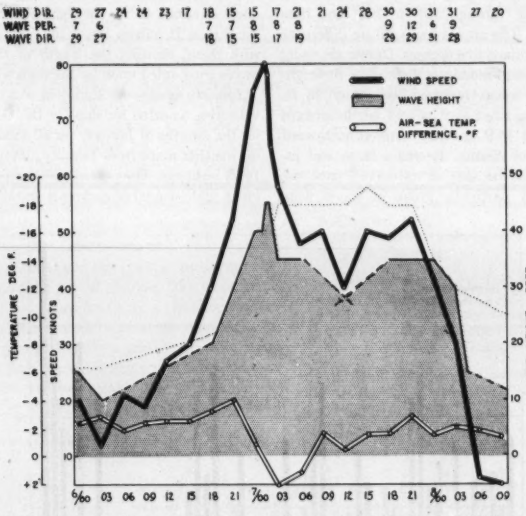

FIG. 5 – Meteorological and oceanographic data for the storm of December 6–8, 1951, recorded at 4YP

ft. Still further downstream at the position of the S.S. *Pennsylvania*, the wave heights were hindcast at 50 ft six hours after this map time.

Windspeed, observed wave height, and air-sea temperature difference which were recorded at 4YP from 00 h 00 m January 8 to 21 h 00 m January 10 are shown on Figure 3. The wind and wave directions in tens of degrees and the ob-

served wave period in seconds are listed at the top. At 18 h 00 m the wind was from 300° with a velocity of 45 knots. For the next 27 hours the speeds averaged about 50 knots with the direction varying only between 290 and 310°. The wave heights rose rapidly to 45 ft between 00 h 00 m and 03 h 00 m on the 9th. Waves were recorded at 45 ft or over for 18 consecutive hours, reaching 48 ft at 15 h 00 m. The large degree of instability during the height of the storm is illustrated by the air-sea temperature difference averaging ten degrees. At 03 h 00 m the lapse rate exceeded the dry adiabatic to a height of 5000 ft.

Comparison of severe storms—The records of two other very severe storms are presented for comparison with the *Pennsylvania* storm. These storms met both Criterion I and II. The record for a storm with higher average winds for a longer duration is presented in Figure 4. Weather Ship 4YP recorded a wind speed of 55 knots for 24 hours beginning at 06 h 00 m on January 20, 1951. However, during this period the wind backed uniformly from 40° through 360° to 290° and then veered to 340°. The air-sea temperature difference averaged only minus five degrees. Due to changing wind direction and moderate instability the highest significant waves reported were only 26 ft. This storm intensified as it moved northeastward to the south of 4YP and then curved northward into the Gulf of Alaska. It was a large and intense storm, and because of its curved path the winds over any particular group of waves were continually changing direction. From the latter half of the 21st until the 23rd, it was quasi-stationary, but during this period it weakened with decreasing wind speeds over the entire Gulf.

The record for a storm with much higher wind velocities is presented in Figure 5. The wind speed rose from 40 knots at 18 h 00 m on December 6, 1951 to 80 knots at 01 h 20 m on the 7th. Waves moving from the south increased rapidly at 4YP from a reported height of 20 ft up to 45 ft at 01 h 20 m and then dropped back down to 35 ft by 03 h 00 m. The wind direction varied from 150 to 210°. The air-sea temperature difference was small and even attained a small positive value at 03 h 00 m on the 7th. A second group of waves with a reported significant height of 35 ft moved into the area from the northwest at 18 h 00 m on the 7th. This storm moved northeastward as it intensified. It passed to the north of 4YP and then filled rapidly. The highest winds were confined to a narrow zone to the east and southeast of the storm center. This zone was moving at an angle of about 40° to the right of the direction of the waves. It moved across the waves rather than with them, limiting the length of time that the waves were acted upon by the high winds.

January winds—A tabulation was made of wind velocities reported by ships in the Gulf of Alaska for the months of January for all available historical weather maps from January, 1900, to January, 1952, inclusive. The percentage of reports of Beaufort 8 (gale winds) or greater is shown in graphical

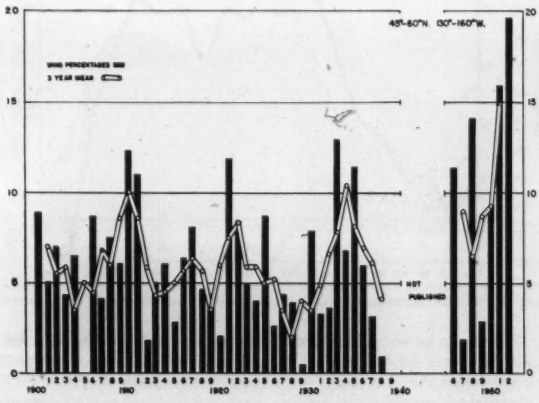

FIG. 6 – Percentage of winds of force 8 or greater which were reported by ships in the Gulf of Alaska during January 1900–1952

form in Figure 6. Fetch and duration were not considered in this tabulation but Beaufort 8 winds with sufficient fetch and duration are capable of setting up waves with significant heights of 30 ft or more [*Munk and Arthur*, 1951]. This tabulation serves as a general measure of the storminess in the Gulf of Alaska for a longer period of time than the more intensive storm survey did.

The extreme range in the percent of gale winds from 0 to 19.7 pct was larger than anticipated. January of 1905 and 1939 were notably calm while January of 1951 and 1952 were considerably stormier than the average. A three-year running mean was computed and plotted in Figure 6.

From 1900 to 1939 the three year running mean suggests a 12-year cyclic pattern with peaks in 1910, 1922, and 1935. It is interesting to note that *Cornish* [1934] reports that the *Ascanius* logged mountainous seas in this region in 1921, and *Witmarsh* [1934] reported the highest carefully recorded wave ever reported in 1933 while on a path just south of the area considered in this paper.

An attempt to forecast on the basis of the 12-year cycle would have failed if the cycle were extrapolated to 1952. With 19.7 pct gale winds, 1952 had three times the average percentage, but would have fallen on the lowest part of the cycle.

Conclusions—Several factors combined in a unique fashion to produce an extreme in wave heights and duration during the *Pennsylvania* storm. Waves first generated to the rear of the moving storm entered the highest wind speed zone of the storm when it was quasi-stationary. The asymmetry of the storm was such that the waves were acted upon by winds from the same direction for a long period of time. The great instability of the air may have been a contributing factor to the extreme wave heights; the supposition is, other things equal, that a greater shearing stress is produced on the water surface in unstable than in stable air. There is a great deal of variability in the intensity of storms in the Gulf of Alaska from winter to winter. The years with very severe storms appear to be grouped together. These groups of bad winters have been separated by years with few, if any, severe storms. There is a suggestion of a twelve year periodicity in the intensity of storms, but the storms of the winter of 1951–52 which stand out as the most severe group examined for the Gulf of Alaska, are completely out of phase with the cycle.

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An Electronic Sea-Wave Recorder

V. Narayana Rao

Abstract—This article describes a surface type of sea-wave recorder which is based on the principle of the variation in the capacitance between the sea water and an insulated wire placed vertically in it with changes in the level of the sea water. This change in capacitance is used to modulate the frequency of an oscillator. An electronic unit is used for recovering from the frequency modulated signal an electrical voltage which is an exact replica of the sea wave. This electronic unit is described in detail. The type of recording suitable for various applications and also the performance characteristics of this instrument are also discussed.

Introduction—In order to understand the nature of the sea waves, their characteristics, their influence, and the information they convey, it is necessary to record these waves and to carry out an analysis to estimate their spectrum, significant wave height, and mean significant period. Similar wave recording is also required for experimental studies on models of harbors and beaches. Several types of wave recorders and also techniques for processing the records have so far been developed for these applications [*Tucker*, 1953; *Caldwell*, 1948]. These wave recorders fall broadly into three categories: (1) underwater types, (2) surface types, and (3) aerial types. In the underwater type of installation an inverted echo sounder is sometimes used, but more often a pressure-actuated device is employed. This type utilizes the pressure change at the sea bottom at a depth between 40 to 80 ft due to the passage of the wave. The pressure change can be measured by bourdon tubes, strain gages, or piezoelectric and moving coil transducers. Since the bottom-pressure fluctuation p, corresponding to a surface wave of amplitude a_0, is given by $p/a_0 = \text{sech}\ (2\pi h/\lambda)$, where h represents the depth of the water, and λ the wave length [*Tucker*, 1953], this type of pressure actuation will not respond to waves of short wave lengths. Although this factor is not a serious disadvantage where the main interest is in the longer waves, such as in the study of long swell from a distant storm, it is necessary to use other types of recorders where a true picture of the surface wave is desired. For experimental studies on models, the surface type is the only one that can be used.

There are several types of wave recorders of the surface type. Most of them use the property of conductivity of the sea water. The parallel wire gage and the step resistance gage type of wave recorders [*Caldwell*, 1948] depend on the variation in resistance between a pair of wires with changes in the level of sea water.

The wave recorder described in this paper is a surface type of wave recorder and is based on the principle that the capacitance between the sea water and an insulated conductor placed vertically in it varies with the changes in level of the sea water. An instrument based on this principle where the change in capacity is measured directly has been described by *Tucker* [1953]. The instrument described here utilizes a different technique for recording the variations in the capacitance and has a high sensitivity and flexibility in its application.

General Description of the Instrument

Capacitance-wire electrode—The capacitance-wire electrode used in this instrument consists of a straight wire surrounded by a polythene insulator of uniform thickness. This is obtained by removing the outer protective covering as well as the outer shield of a standard coaxial cable, such as RG-9u, used in u h f work. The central conductor along with the polythene insulator is passed through a tight fitting glass tube. This, when dipped in sea water, forms the inner conductor. A thick copper wire fixed to a zinc grid at the other end is dipped in the sea water, and this connects the outer conductor, which is the sea water, to the measuring device. For tests in the laboratory the electrodes were placed in a large glass tube which was filled with salt water to the desired level (Fig. 1).

Measurement of variation in capacitance—Figure 2 shows the schematic circuit diagram of the instrument. The technique employed here for recording the variation in capacitance of the electrode is to use this capacitance across the tank circuit of a self oscillator so as to produce a frequency modulation of the oscillator output and then to demodulate the frequency modulated signal so as to convert it into an electrical voltage which is a replica of the sea wave. With the type of capacitance wire used here, the capacitance change per foot varia-

tion in the level of water is 22 $\mu\mu f$. If the oscillator employed is an audio one, the change in frequency produced by this variation in capacitance is too small to be any use. Hence a radio frequency oscillator operating at a frequency of about 1 mc/s is used. The oscillator is a conventional Hartley oscillator and is well shielded to avoid stray effects. The tank condenser consists of a 500-$\mu\mu f$ fixed and a 50-$\mu\mu f$ trimmer condenser. The two terminals of the capacitance-wire electrode are connected between the ground and a tap on the tank coil (points 1 and 2 of Fig. 2). If C_s represents the capacitance of the capacitance-wire electrode including the capacitance of the coaxial shielded cable connecting it to the instrument, and C_c the coupling capacitance to the tank coil and C_o the tank capacitance (Fig. 2), it can be shown that the fractional change Δf in the frequency f produced for a change of one foot in the water level (when the electrode is tapped across the full tank coil) is

$$\Delta f/f = \frac{C_c^2 \Delta C_s}{2(C_c + C_s)^2} \Big/ C_0 + \frac{C_c C_s}{C_c + C_s}$$

where ΔC_s is the change in capacitance of the electrode for a change of one foot in the water level. If $C_s = 350$ $\mu\mu f$ and $C_0 = 500$ $\mu\mu f$, Δf is found to be about 0.95 kc/s when C_c is 100 $\mu\mu f$, and 0.32 kc/s when C_c is 50 $\mu\mu f$, for $\Delta C_s = 22$ $\mu\mu f$ and $f = 1$ mc/s.

The function of the coupling capacitance C_c is to control the sensitivity of the instrument and also to reduce the effect of the electrode system on the Q of the tank circuit of the self oscillator. The tap on the oscillator coil can also be used for controlling the sensitivity. The length of the electrode tried out so far has been about six feet, and the length of the coaxial shielded cable connecting it to the instrument has been about 12 ft. Longer lengths of connecting cable can be used, but the sensitivity will be decreased.

Measurement of change in frequency—In order to measure the change in frequency Δf accurately, the output of the variable oscillator is heterodyned into a lower frequency by the use of a fixed r f oscillator operating at about 1 mc/s. This oscillator is also well shielded and has trimmers for adjusting the heterodyned frequency. The heterodyned output, which is in the audio range, is amplified by the voltage amplifier V_4 and fed on to a counter circuit which provides a d c output proportional to the frequency.

The counter circuit suitable for the frequency measurement is of the type used in the frequency-modulated radar altimeter *AN/APN/1* [*Luck*,

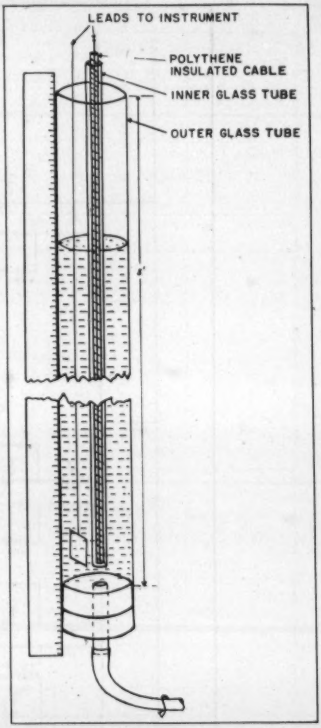

FIG. 1 – Laboratory test set-up of the capacitance-wire electrode

1949]. The heterodyned output from the frequency converter V_2 is amplified by the voltage amplifier V_4 and fed to the limiting stage V_5. Because of the large amplitude of the signal applied to the grid, square wave voltage will be produced at the anode of V_5, and this tube will be switched on and off for half cycles of the input signal. When V_5 is switched off, the capacitance C_s will get charged through the resistor R_0, diode V_7, and the resistor R_1. When V_5 is switched on, C_s discharges through the limiter V_5 and the diode V_6. Part of the current flowing through C_s, when it is getting charged, builds up a voltage across C_1. This voltage is proportional to the number of times C_1 is charged per sec, that is, to the frequency. The voltage output across C_1 is applied to the cathode follower V_8

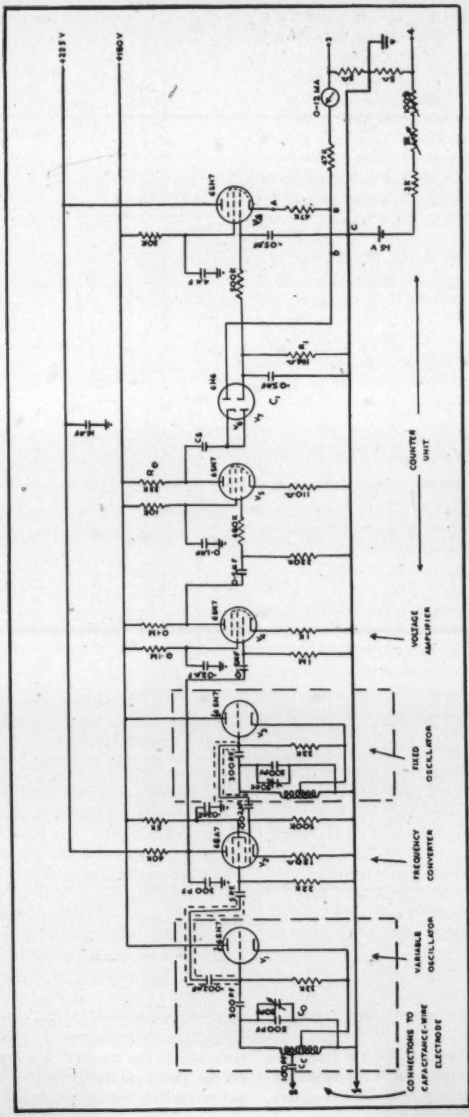

Fig. 2 – Circuit diagram of the electronic unit

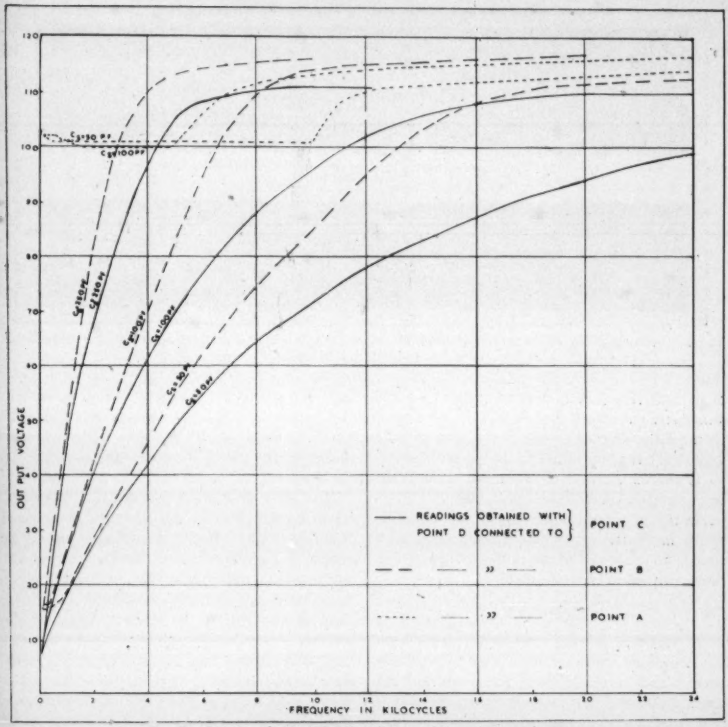

FIG. 3 – Output voltage-frequency characteristics of the counter unit

which provides an output of low impedance. The effect of placing the anode of the discharge diode V_6 at various positive voltages will be to alter the 'output voltage-frequency' characteristics. It is seen from Figure 3 that a fairly linear relationship can be obtained by connecting the point D to B. The effect of C_s on the output voltage-frequency characteristics can also be seen from Figure 3. Large values of C_s give an increased sensitivity but saturation limit is reached for lower frequencies. Optimum value of C_s for this application is 50 $\mu\mu f$, but this value can be increased to 100 $\mu\mu f$ where the frequency range to be covered is lower.

Recording equipment.—The d c output of the cathode follower can be connected to the Y plates of a cathode ray oscilloscope having a d c amplifier. The time base of the oscilloscope should be switched off. The sea waves cause the spot on the oscilloscope to move up and down, and this is photographed, using an oscilloscope camera, on a 35-mm film which is moved at any convenient speed. The type of record obtained while studying the locally generated waves at the entrance to Cochin Harbor is shown in Figure 4. Two speeds have been used for this recording. It is seen that, with this type of recording, waves of any period can be recorded. The output of the cathode follower can also be adopted for recording with a galvanometer type of recorder. The cathode current of the cathode follower V_8 is passed through a five-ohm wire-wound resistor. The standing d c voltage across this is balanced by using another five-ohm resistor through which an adjustable d c current is passed. The output between terminals 3 and 4 of the elec-

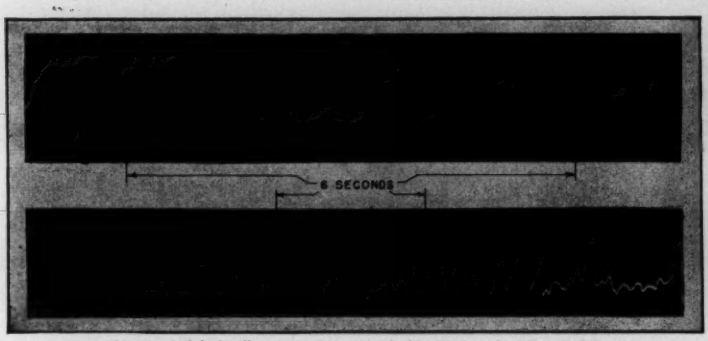

FIG. 4 – Oscillographic record of the locally generated waves at Cochin Harbor; the full-scale deflection corresponds to a wave amplitude of one foot

tronic unit (Fig. 2) can then be applied to a galvanometer recorder of the pen and ink type, such as the Edin recorder, or one of the photographic type. The latter is to be used if the spectrum analysis of the waveform is to be carried out using a wave analyser [*Barber* and others, 1946].

For the instrument power supply, it is desirable to use dry batteries for both filaments and high tension to avoid variations in the frequency due to fluctuations in the main supply.

CONCLUSIONS

(1) This type of wave recorder is suitable both for laboratory study on models of harbors and beaches and for the study of sea waves. For the latter application, it is necessary to fix the capacitance-wire electrode onto a suitable stable supporting structure of the type described by *Gerhardt* and others [1955], at a site where the depth of water is about 40 ft. The length of the capacitance wire should be such that the bottom of the wire is below the lowest wave trough to be expected and the top above the highest crest. The electronic unit of the wave recorder and its dry battery power supplies should be mounted on the structure itself and the leads to the galvanometer recorder taken by means of an armored cable to the shore. A modification can also be carried out so as to use a radio link and to avoid the use of the connecting cable. The electronic unit can then be split into two sections. The section consisting of the capacitance wire and the variable oscillator with a suitable buffer amplifier, dry battery, and aerial, can be located at the supporting structure. The remaining part of the unit, which will consist of an aerial, rf amplifier, converter, fixed oscillator, and the counter, can be located ashore. Thus by radiating the signal at the frequency of the variable oscillator, the use of the connecting cable can be obviated.

(2) This type of wave recorder can respond to waves of all frequencies and can follow the rise and fall of the water surface with negligible error. The overall frequency response is limited only by the galvanometer recording device, and, where steep wave forms are encountered, cathode ray oscilloscope and camera can be used for recording the waves.

(3) The effect of tides can be overcome by introducing a suitable coupling condenser at the grid of the cathode follower. The value of the condenser should be so chosen that waves of the lowest period of interest are passed.

(4) The frequencies of the two oscillators of this unit are fairly stable as battery supplies are in use both for filaments and high tension. The changes in frequency due to changes in temperature and humidity are of such low magnitude and are also spread over such a long time interval that their effect can normally be ignored.

(5) The performance of the capacitance-wire electrode is fairly reliable and comparatively free from the action of the sea water, unlike the other types of surface wave recorders which are very much affected by the sea water.

(6) This wave recorder is extremely sensitive. The sensitivity can be adjusted by varying either the coupling condenser C_c or the tap on the oscillator coil (Fig. 2). With the maximum sensitivity

setting, waves of amplitude of a few inches can be recorded.

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Application of the Solitary Wave Theory to Shoaling Oscillatory Waves

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Abstract—The celerities of shallow-water waves were studied in the laboratory as a function of wave height and wave length or period. The experimental celerities were compared to the theoretical values obtained from the oscillatory (Stokian) wave theory, the solitary wave theory, and the cnoidal wave theory. The last was found to be experimentally valid for the transition but is practically inapplicable for prediction. On the basis of this comparison, an effective wave length could be defined below which the Stokian theory applies, and above which the solitary wave theory gives better results.

Introduction—Studies of the transitional waves between oscillatory and solitary waves have been pursued at the Hydrodynamics Laboratory of the Massachusetts Institute of Technology to clarify the application of solitary wave theory to oscillatory wave problems. Some authorities, notably *Bagnold* [1947] and *Munk* [1949] have suggested the use of the relatively simple solitary wave theory in water where the depth to wave length ratio becomes sufficiently small. But *Ippen* and *Kulin* [1955] have shown that breaking heights and depths of long-period waves are not adequately predicted by the solitary wave theory.

The results of the experimental study are applied to define a limiting or effective wave period, separating zones of applicability of the solitary and of the oscillatory wave theories. This limiting wave period is obtained by comparison of values of theoretical wave celerities with experimental celerity, since celerities are relatively easily determined and serve as an indication of the prevalent wave characteristics.

Theoretical considerations—Within any one theoretical wave development, the expressions for celerity, profile, energy, etc., are consistent with the original assumptions. Therefore, the validity of the theoretical wave celerity is taken to be an indication of the applicability of the particular theory to the other wave properties.

There are three wave theories which apply to waves in shoal water: herein called oscillatory, cnoidal, and solitary, following *Keulegan's* [1950] presentation. Stokes' theory for oscillatory waves gives

$$C_o^2 = gd(L/2\pi d)(\tanh 2\pi d/L) \qquad (1)$$

Korteweg and deVries present the cnoidal theory

$$C_c^2 = gd(1 + h_1/d)(1 - h_2/d)(1 - h_3/d) \qquad (2)$$

and Boussinesq's theory for solitary waves is

$$C_s^2 = gd(1 + H/d) \qquad (3)$$

where

- C = wave celerity
- L = wave length
- d = still water depth (SWD) referred to still water level (SWL)
- H = wave height
- h_1 = height measured from SWL to crest
- h_2 = height measured from SWL to trough
- h_3 = a reference quantity of analytical significance only, having the dimensions of length

Munk [1949, p. 413] uses 'depth below trough level' in (3). For a true solitary wave, this is identical with SWD. In this paper, SWD is used throughout to provide a common reference depth, and because depth below trough level cannot readily be predetermined in practice.

Higher approximations of Stokes' theory for oscillatory waves are not considered here, because the added terms of higher approximations 'overcorrect' the celerity for very small values of H/L and d/L. *Savage* [1954] has shown by a statistical analysis that (1) fits the experimental data better than the higher approximations when $d/L < 0.1$.

The three expressions for wave celerity are shown on Figure 1 as dimensionless plots of $C/\sqrt{gd}$ versus L/d, at five representative H/d ratios.

Experimental equipment—The experiments were carried out in a glass-walled flume, 90 ft long, 2½ ft wide and 3 ft deep. Waves were generated at one end of the flume by a hydraulically operated, vertical plate, piston-type generator. [*Ippen* and *Eagleson*, 1955]. A beach with a slope of approximately 1/15 was installed at the other end of the flume as a wave-energy dissipator. The motions of the generator may be of almost any type, that motion being prescribed by a specifically designed control cam. The cam motion actuates a hydraulic piston which in turn actuates the generator plate. The cam seen in Figure 2 is driven by a variable speed DC motor. The follower-arm normal to the

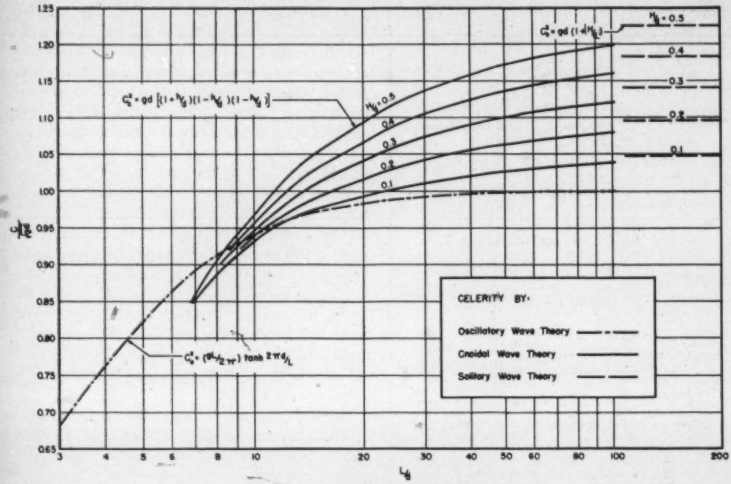

FIG. 1 – Wave celerity theories

plane of the cam, and rolling along the cam's periphery, actuates the hydraulic valve (seen in the lower left portion of the figure) by way of a linkage and mechanical feedback system. The hydraulic valve controls the flow of oil in the cylinder directly connected to the generator plate. On Figure 3 is seen a schematic diagram of a control cam and the associated motion of the wave generator plate.

Each revolution of the control cam causes the generator to move through one complete cycle, moving the plunger through stroke S, creating a wave of period T. Because a great deal of water must be piled up by the forward stroke of the generator plate in a short time, to create a measureable wave with long wave period, the ratio of forward stroke time to total wave period, t_1/T, must be less than $\frac{1}{2}$, which is the value for the usual simple harmonic motion. The positive slope of the S-T curve indicates forward motion of the generator plate, and the negative slope indicates the return motion of the generator. The motions desired in these experiments were produced by using a specially designed set of eight cams. The ratio of t_1/T is determined by the particular cam used, and these ratios range algebraically from $\frac{1}{16}$ to $\frac{8}{16}$.

The shape of the cams was determined after a time-motion study of the wave generator [*Taylor*, 1956] which produced reasonably pure solitary waves. The motion of this generator was essentially sinusoidal for solitary waves over the complete range of H/d ratios, $(0.1 < H/d < 0.6)$. Therefore, the peripheral shape of a cam is formed

FIG. 2 – Control mechanism for wave generator motion

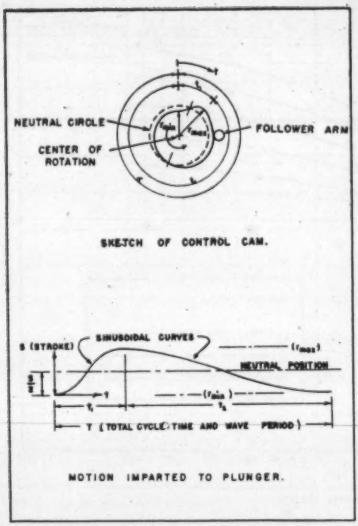

FIG. 3 – Control and motion of wave generator

of two one-half sine waves of length ratios determined by the t_1/T ratio. The amplitude of the cam waves was fixed by the limits of the hydraulic circuit of the generator.

Because of the difficulty in setting up conventional machines to accurately cut these cams, it was decided to use the numerically-controlled, automatic milling machine at MIT. The algebraic equations described by the loci of the milling machine's cutting tool center to properly cut the cams were programmed through the digital computer, Whirlwind I, at MIT. The output of the computer was the binary-punched tape that became the input to the control unit of the milling machine. Taylor discusses this procedure in detail.

By using the series of control cams and varying the angular velocity of the cams, waves can be generated with identical forward motions of the generator plate and different return motions, thus with different wave periods, depending on the cam being used. By trial and error, this procedure allows for generation of solitary waves, oscillatory waves, and many transition waves, all with the same H/d ratio. The return stroke of the wave generator causes very little disturbance when using the cam with $t_1/T = \frac{1}{16}$, and essentially solitary waves are thereby produced.

Experimental procedure—All the tests were run with a still water depth d of 1.5 ft. The celerity was determined by measuring the time of travel of a wave form between two capacitance-type profile probes connected to a Model 150 Sanborn oscillograph recorder. These probes were located ten feet apart in the constant depth portion of the wave flume, approximately 40 ft from the wave generator.

Two, and sometimes three, generation times t_1 were used with each control cam, of approximately 0.50, 1.17, and 1.33 sec. The stroke of the wave-generator plate S was varied to generate four heights of waves at each t_1 and t_1/T. The generator was operated such that the highest one of the waves was near the limit at which waves would break on leaving the generator plate, and the lowest was one for which the form was still identifiable. Thus, the H/d ratio was varied over a range from 0.05 to 0.50.

The data obtained were plotted to show curves of $T\sqrt{g/d}$ versus $C/\sqrt{gd}$, varying with H/d, the dimensionless wave period, celerity, and height, respectively. Figure 4 is a typical plot. Curves were

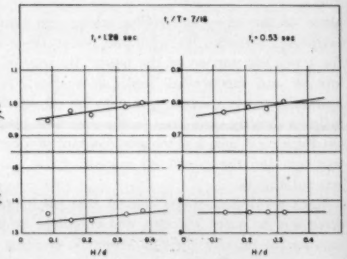

FIG. 4 – Sample data plot—dimensionless

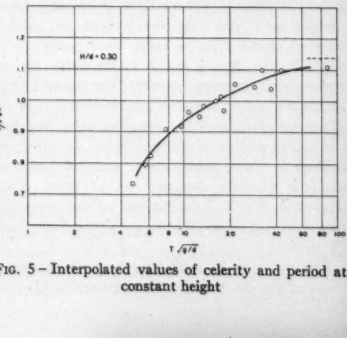

FIG. 5 – Interpolated values of celerity and period at constant height

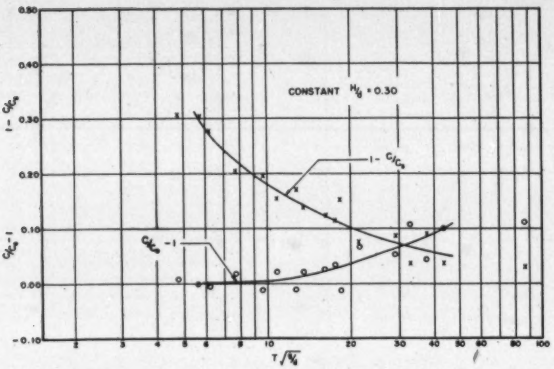

FIG. 6 – Definition of effective wave period by comparison of celerities at H/d = 0.30

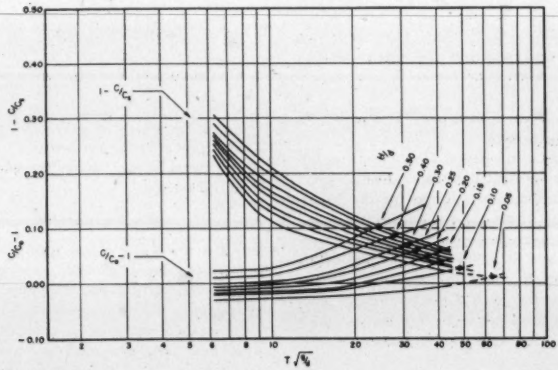

FIG. 7 – Definition of effective wave period by comparison of celerities at H/d = 0.05 to 0.50

fitted by successive bisection of the segments connecting observed points.

The scatter in these data was primarily due to the finite length of the flume, with its attending reflection of waves back through the test section. For the longest wave lengths, of approximately 150 ft, the wave profile was not yet stable when measured some 40 ft from the generator, or less than one-third of the wave length. As L/d decreased, the stability of the form of the wave increased, so that most of the data were obtained from waves of good form.

Results—From the curves like Figure 4, values of $T\sqrt{g/d}$ and $C/\sqrt{gd}$ were interpolated at the specific H/d ratios of: 0.05, 0.10, 0.15, 0.20, 0.25, 0.30, 0.40, and 0.50. Figure 5, for the ratio 0.30, is typical. The experimental values of celerity C were then compared with the theoretical values C_o, C_c, and C_s, defined by (1), (2), and (3). Although the celerity in the transitional region between the oscillatory and solitary waves is defined with reasonable accuracy by the cnoidal theory, it involves the solution of elliptic integrals, and is difficult to apply.

Therefore, functions of C/C_s and C/C_o are plotted against $T\sqrt{g/d}$ for particular values of

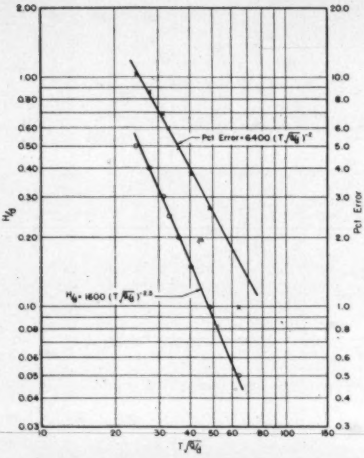

FIG. 8 – Relative wave height and celerity error at effective wave period

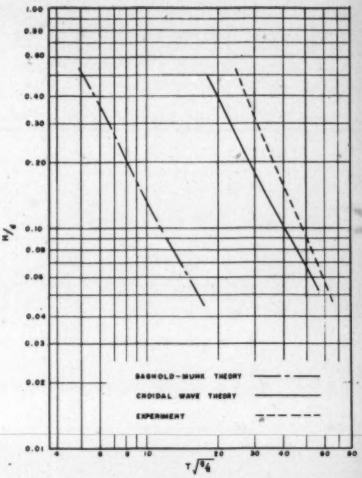

FIG. 9 – Comparison of effective wave period theories

H/d. Figure 6 is one of these plots, at H/d of 0.30, to illustrate the behavior.

It is seen that as the period of wave is increased, the celerity by the oscillatory theory diverges from, and the solitary theory converges to, the experimental celerity. At the point of intersection of the two curves, the percentage of error by either theory is the same, and it is the wave period at this intersection which is here defined as the effective wave period, at the given H/d ratio. Similar plots were made for the other seven H/d values, and a superposition of the eight sets of curves is shown in Figure 7.

It is seen that the effective wave period $T_e\sqrt{g/d}$, the intersection of a pair of curves at the same H/d value, increases with decreasing H/d ratio. These values of $T_e\sqrt{g/d}$ are now plotted against H/d in Figure 8, which thus gives a complete definition of the effective wave period. Also plotted on this figure is the maximum percentage of error between the theoretical and experimental celerities, which by definition occurs at the effective wave period. The equations of these lines may be stated as

$$H/d = 1600\,(T\sqrt{g/d})^{-2.5} \qquad (4)$$

for the local wave height at the effective wave period, and

$$Pct\ error = 6400\,(T\sqrt{g/d})^{-2} \qquad (5)$$

for the maximum error in celerity.

From Bagnold and Munk, the effective wave period is defined as

$$T\sqrt{g/d} = 2\pi/M \qquad (6)$$

where $M = 3\sqrt{H/d}$ is a first approximation. This theory gives values of effective wave period four to five times shorter than the experimentally defined wave period.

Another theoretical expression for effective wave period has been derived from comparison of celerities with cnoidal theory celerity. From calculations analogous to those defining the experimental effective wave period, the cnoidal theory effective wave period has been defined as the period at which $(C_c/C_e - 1)$ is equal to $(1 - C_c/C_e)$. The expressions for C_0, C_c, and C_e are those given in (1), (2) and (3).

On Figure 9 are plotted the three definitions of effective wave period: from the experimental, from the cnoidal theory, and from the Bagnold-Munk theory, respectively.

Some breaker data of solitary waves, from *Ippen* and *Kulin* [1955] have been converted to equivalent oscillatory wave data by means of the experimental effective wave period, and were then compared with the breaking wave data of *Iversen*

[1952]. The agreement is good, and investigation of the application of the experimentally defined effective wave period is continuing.

Conclusions—The cnoidal wave theory describes wave celerity in water depths at which L/d varies from approximately 10 to 100, with reasonable accuracy. However, in practice, the quantities of the theory h_1, h_2, and h_3 are difficult to derive.

The effective wave period (or length) defined by Bagnold or Munk is inadequate for prediction of breaker characteristics on the basis of available experimental evidence [*Ippen* and *Kulin*, 1955]. The equations shown for relative height (4) and per cent error of celerity (5) as functions of dimensionless period provide a practical criterion for effective wave period.

If H/d and $T\sqrt{g/d}$ ratios of a shoaling wave problem are such that the area to the left of the H/d curve (Fig. 8) is encountered, then the oscillatory theory will give more accurate results than the solitary theory, and vice versa.

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Axial Slope of Sea Level in Chesapeake Bay*

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Abstract—The north-south variation in axial slope of monthly mean sea level in Chesapeake Bay was investigated by means of tide-gage records. Data from three stations indicate a marked similarity between axial slopes over the northern and southern halves of the bay.

Chesapeake Bay, extending 150 mi north from its mouth and being unusually straight and narrow, lends itself admirably to an investigation of its longitudinal surface-slope by means of tide-gage records from three stations along its western shore (Fig. 1). The purpose of the present study is to determine whether such axial sea-level slope, with tidal oscillations eliminated, is the same over the northern and southern halves of the bay, without regard for the factors which cause it to vary. The small ratio of width to length of the bay (less than 0.1 on the average) implies that the effect of transverse gradients on vertical surface displacements will be relatively negligible. Another feature of the bay, advantageous to this study, is the identical mean depth of about 31 ft in the two sectors.

The data consisted of monthly means of sea level for Baltimore (Fort McHenry), Solomons (inside the mouth of the Patuxent River), and Hampton Roads (Sewells Point at the Norfolk Naval Base). These records spanned the greater part of the period 1940 through 1955. The use of monthly means was dictated partly by the availability of the data in this form. But equally important, a monthly average eliminates all distortions of the sea surface due to semi-diurnal and diurnal, as well as fortnightly and monthly, constituents of the astronomical tide.

The treatment of the original data was based on three considerations: to eliminate sea-level variations which originate in the open Atlantic and would have the same magnitude throughout the bay; to eliminate the effect of slow differential rising or subsidence of coastal regions near the three tide gages; and to convert the tabulated heights, based on an arbitrarily selected zero datum for each station, to comparable sets of anomaly values. First, 12-month running means were computed for the entire sets of data. Each 12-month mean was considered applicable to the seventh month in its particular series and was then subtracted from the observed value of that month.

FIG. 1 – Location of selected tide-gage stations

The residual is designated 'monthly sea level anomaly' (MSLA).

The MSLA difference between two stations is directly proportional to the sea-level slope between them. However, the slope thus found is not an absolute one but is referred to any long-term

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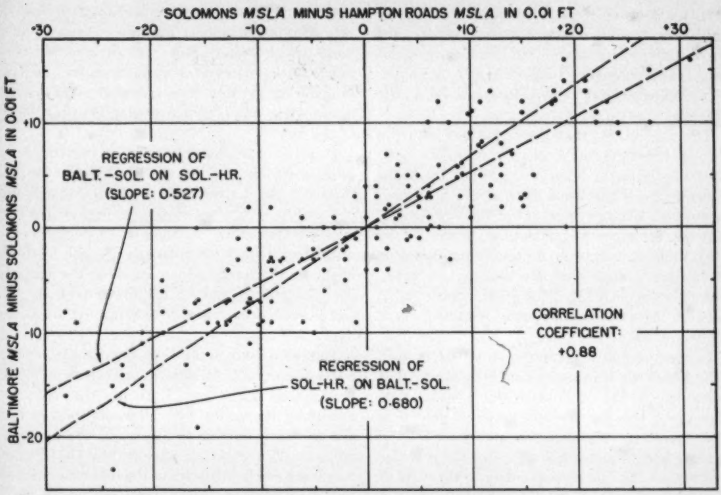

FIG. 2 – Plot of monthly sea level anomaly differences

equilibrium configuration which the sea surface might have. The free surface may deviate permanently from an equipotential one as a result of density distribution of the bay waters, river outflow, wind stress, and barometric pressure gradients. Monthly changes in slope will reflect only the deviations of these four factors from their annual means. The year-to-year variations of the annual means can be considered at least one order of magnitude smaller than the monthly fluctuations of the same parameters and can be safely neglected over a period of a few decades. The question of a permanent slope in the bay might be resolved by geodetic leveling if a completely unwarranted amount of effort were devoted to it. But, as pointed out to the writer by personnel of the U. S. Coast and Geodetic Survey, precise leveling data now in existence are inadequate for the purpose despite their high order of accuracy.

Each monthly mean of sea level is given to the nearest hundredth of a foot and represents the average of about 700 hourly values read to the nearest tenth of a foot. The 12-month means were also determined to the nearest hundredth. With an uncertainty of ± 0.005 ft in both these values, MSLA has a possible error of ± 0.01 ft and the difference between two MSLA's will lie within the range, ± 0.02 ft. To maintain this degree of accuracy, no MSLA's were determined for any month in which the tabulated mean sea level at one of the stations was an inferred value. On the other hand, a 12-month mean which included one inferred value for Baltimore or Solomons and two inferred values for Hampton Roads was considered acceptable. The less stringent requirement for Hampton Roads resulted from the fact that missing data there could be inferred with considerable accuracy from the records of the Old Point Comfort tide gage, only 3½ mi distant.

Because of these criteria, a substantial gap in the data occurs in 1942 and 1943 where there were 14 consecutive months of inferred values at Hampton Roads. Nevertheless, a total of 153 months was available for analysis, of which only 35 months included inferred values in the 12-month means. For these 153 months, MSLA differences between Baltimore and Solomons and between Solomons and Hampton Roads were computed and plotted against each other in Figure 2.

Despite the considerable scatter of the points, it is apparent that their distribution is approximated by a straight line through the origin. Linearity through the origin merely indicates a constant ratio between the surface slopes of the northern and southern halves of the bay. A constant slope over the entire length of the bay must also satisfy the condition that the MSLA differences are in the same ratio as the respective distances between the

stations. Because of the north-south trend of the bay's axis, the differences in latitude between the three stations furnish an accurate measure of this ratio. These differences are, Baltimore to Solomons, 57 mi, Solomons to Hampton Roads, 82 mi, a ratio of 0.695.

The assumption that the regression lines run through the origin was verified by means of a least-squares adjustment of the form $y = a + bx$. As the intercept a was much smaller than 0.01 ft, it could be omitted. The regression of the MSLA difference between Solomons and Hampton Roads on the MSLA difference between Baltimore and Solomons gives a line of slope 0.680 and the converse regression one of slope 0.527. The correlation coefficient between the sea-surface slopes of the two parts of the bay is $+0.88$.

In view of the uncertainty of ± 0.02 in each MSLA difference value, it can be assumed that every point in the graph lies within a square, 0.04 ft on a side. It is then a simple matter to determine how many of these squares are crossed by a straight line through the origin. This test was carried out for the line corresponding to the ratio of distances between the stations, with a slope of 0.695, and for the line corresponding to the geometric mean of the two regression curves, with a slope of 0.599. For the former, 60 pct of the squares intercept the line, for the latter, 66 pct.

Some preliminary results of a more comprehensive study, now in progress, indicate that wind stress is the dominant cause of changes in sea surface slope in Chesapeake Bay. Since mean monthly wind stress values show substantial differences between the northern and southern ends of the bay, it may well be that the scatter of points in the graph is due largely to this geographical variability of the wind.

It can be concluded that there is a high degree of positive correlation between the slopes of the sea surface in the northern and southern halves of the bay and that the slopes are nearly equal. The two regression lines show the slope in the northern part of the bay to be between two and 24 pct. less than in the southern part. However, since the independent variable cannot be identified, tests for the significance of the regression coefficients are meaningless.

Thanks are due to the U. S. Coast and Geodetic Survey, especially to numerous members of the Division of Tides and Currents, not only for furnishing the writer with all available data but also for many helpful discussions of the problems involved. This work was supported by the Office of Naval Research (Geophysics Branch), the State of Maryland (Department of Research and Education), and the Commonwealth of Virginia (Virginia Fisheries Laboratory).

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Pseudo-Characteristics

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Abstract—The pseudo-characteristics are defined as the lines along which the dependent variables in nonhomogeneous equations have the same relationship as the similar variables in the corresponding homogeneous equations. A sample computation of water levels caused by wind stresses, using the pseudo-characteristics, is included.

Introduction—The characteristics of a set of hyperbolic partial differential equations have many useful and interesting properties [*Courant* and *Friedrichs*, 1948]. If the set of equations is homogeneous, the characteristics are lines along which there are fixed functional relationships between the dependent variables. If the set of equations is nonhomogeneous, then certain relationships between the dependent variables and their derivatives are true along the characteristics. These relationships and the companion properties of the characteristics can be derived rigorously, following basic mathematical procedures set forth in the literature [see, for example, *Courant* and *Hilbert*, 1937, p. 290 ff., or *Freeman*, 1951]. There is another very important set of lines, which, in the homogeneous equations, coincides with the characteristic lines. These are the lines along which the relationship between the dependent variables in the homogeneous case holds. We name these lines the 'pseudo-characteristics.' Since the relationships between variables are difficult to express in general cases, the importance of these lines will be emphasized with a particular example.

Discussion—The set of equations for one-dimensional, wind-driven flow of water in a very shallow basin or for one-dimensional flow of air under an inversion can be written as follows

$$\partial u/\partial t + u\,\partial u/\partial x = -\gamma\partial h/\partial x + fv + \tau_x/\rho h \quad (1)$$

$$\partial v/\partial t + u\,\partial v/\partial x = -fu \quad (2)$$

$$\partial h/\partial t + u\,\partial h/\partial x + h\,\partial u/\partial x = 0 \quad (3)$$

The oft-repeated definitions of the quantities in these equations are

- x the space coordinate
- t the time
- u the velocity in the x direction
- v the velocity normal to the x direction
- h the height of the fluid above the bottom
- f the Coriolis parameter
- γ a buoyancy factor $= g(\rho - \rho')/\rho$
- ρ the density of the lower fluid
- ρ' the density of the upper fluid
- τ_x the stress of the wind in the upper fluid
- g the acceleration of gravity

By the substitution of $c = \sqrt{gh}$ in (1) and (3) and by multiplying (3) by g/c, the following two combinations of (1) and (3) can be made.

$$\partial(u + 2c)/\partial t + (u + c)\partial(u + 2c)/\partial x = fv + g\tau_x/\rho c^3 \quad (4)$$

$$\partial(u - 2c)/\partial t + (u - c)\partial(u - 2c)/\partial x = fv + g\tau_x/\rho c^3 \quad (5)$$

To make the system complete, we add (2).

These equations are nonhomogeneous; that is they contain more than one power of the partial derivatives. If we study a case in which $f = 0$, $\tau_x = 0$, and $v = 0$, then the equations become homogeneous. Under these conditions, the equations become

$$\partial(u + 2c)/\partial t + (u + c)\partial(u + 2c)/\partial x = 0 \quad (6)$$

$$\partial(u - 2c)/\partial t + (u - c)\partial(u - 2c)/\partial x = 0 \quad (7)$$

Using the similarity of these expressions to the material derivative, they can be expressed

$u + 2c$ = constant at a point moving with speed $dx/dt = u + c$

$u - 2c$ = constant at a point moving with speed $dx/dt = u - c$

$dx/dt = u + c$ and $dx/dt = u - c$ are the characteristic lines of the differential equations (6) and (7). As such, they have desirable mathematical properties, such as being the lines along which discontinuities can occur in the derivatives. When we study (2), (4), and (5), we find that we can write by inspection $d(u + 2c)\,dt = fv + g\tau_x/\rho c^3$ at a point moving with speed $dx/dt = u + c$ and $d(u - 2c)\,dt = fv + g\tau_x/\rho c^3$ at a point moving with speed $dx/dt = u - c$. It can be shown by methods outlined by *Courant* and *Friedrichs* [1948] that $dx/dt = u + c$, and $dx/dt = u - c$ are the characteristic lines of (1) and (3) in the $x - t$ plane. They are not, however, lines along which $u + 2c =$ constant, and $u - 2c =$ constant. There are many advantages in following lines along

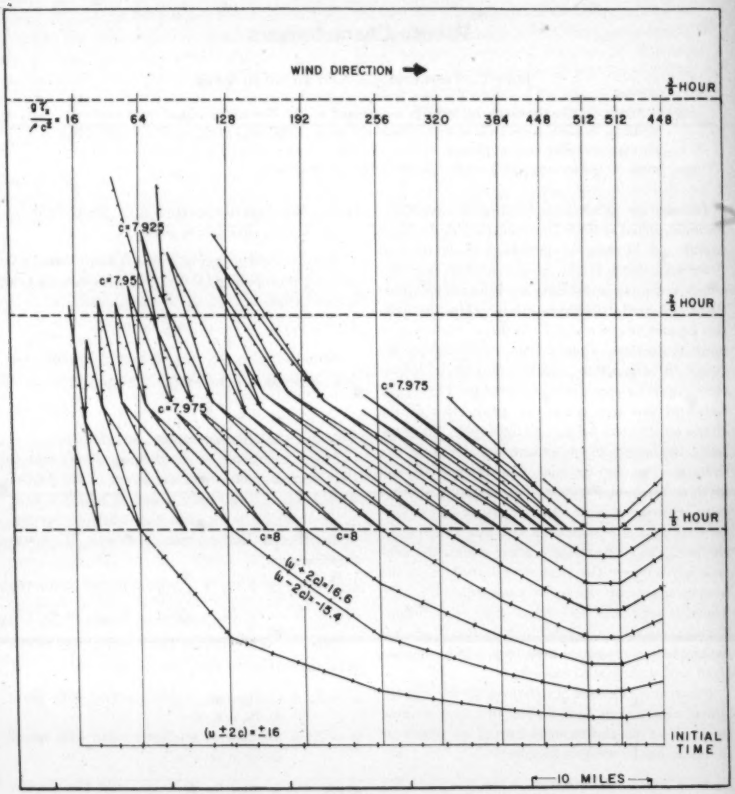

FIG. 1 – Pseudo-characteristics diagram for wind blowing across a level-bottomed basin of water; wind speeds can be found from the values of $g\tau_x/\rho c^2$; positive and negative tick marks show where $(u + 2c)$ and $(u - 2c)$ coincide and are separate; note the area of generation of new lines of $(u + 2c)$ and $(u - 2c)$ in the region of maximum stress

which a fixed functional relationship holds. The lines along which $u + 2c$ = constant and $u - 2c$ = constant will be defined as the pseudo-characteristics.

Note that if $\partial(u + 2c)/\partial x \neq 0$ and $\partial(u - 2c)/\partial x \neq 0$, then we can write (4) and (5) in the following form

$$\partial(u + 2c)/\partial t + \left[u + c - \left(fv + \frac{g\tau_x}{\rho c^2}\right) \Big/ \frac{\partial}{\partial x}(u + 2c)\right] \partial(u + 2c)/\partial x = 0 \quad (8)$$

$$\partial(u - 2c)/\partial t + \left[u - c - \left(fv + \frac{g\tau_x}{\rho c^2}\right) \Big/ \frac{\partial}{\partial x}(u - 2c)\right] \partial(u - 2c)/\partial x = 0 \quad (9)$$

Again, noting the analogy with the material derivative, we can write $u + 2c$ = constant at a point moving with speed

$$dx/dt = u + c - \left(fv + \frac{g\tau_x}{\rho c^2}\right) \Big/ \frac{\partial}{\partial x}(u + 2c) \quad (10)$$

$u - 2c$ = constant at a point moving with speed

$$dx/dt = u - c - \left(fv + \frac{g\tau_x}{\rho c^2}\right) \Big/ \frac{\partial}{\partial x}(u - 2c) \quad (11)$$

Thus we have found the pseudo-characteristics or the lines along which $u + 2c$ and $u - 2c$ are constant. If $\partial(u + 2c)/\partial x = 0$, then $\partial(u + 2c)/\partial t = fv + g\tau_x/\rho c^2$, and, if $\partial(u - 2c)/\partial x = 0$, then $\partial(u - 2c)/\partial t = fv + g\tau_x/\rho c^2$. Looking at an actual computation we can see that when the pseudo-characteristic becomes horizontal in the $x - t$ plane in a region where $fv + g\tau_x/\rho c^2$ has a finite value, new pseudo-characteristics for new values of $u + 2c$ will be created.

The niceties of the computing method are better shown by an example of a water level problem.

Example—The hypothetical case illustrated in Figure 1 concerns a line of thunderstorms which remains stationary over a large basin of shallow water with the following initial conditions

$$u = 0$$

$$c = 8 \text{ kts}$$

$g\tau_x/\rho c^2$ = as shown by the dashed vertical lines in Figure 1.

For simplification, v is neglected.

The computation has not been carried to completion, since its primary purpose is to illustrate the procedure. As was previously discussed, with these initial conditions and after the first small time increment at ½ hour

$$\Delta(u + 2c) \approx \Delta(u - 2c) \approx g\tau_x/\rho c^2 \Delta t \approx u$$

since c remains almost constant.

At t = ½ hour, values of $(u + 2c)$ and $(u - 2c)$ have been generated. Of special interest is the way that new values are generated in the vicinity of the stress maximum.

To find the new slope, the gradients of $(u + 2c)$ and $(u - 2c)$ were divided into the value of $g\tau_x/\rho c^2$ and subtracted from $(u + c)$ and $(u - c)$, respectively. As in the method of characteristics, the result dx/dt is the distance along x that the pseudo-characteristics move in one hour.

Since the pseudo-characteristics are lines of constant $(u + 2c)$ and $(u - 2c)$, it is easy to find u and c for any intersection. Knowledge of u and c for the points allow computation of the next time step.

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An Analysis of Surface Energy During the Ablation Season on Lemon Creek Glacier, Alaska*

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Abstract—The purpose of the present study has been to perform an empirical investigation of the energy transfer at an isothermal, melting snow surface and its relationship to observed meteorological parameters, using more refined instrumentation and methods of observation than were available in earlier, similar investigations by H. U. Sverdrup and C. C. Wallen.

The thickness of the surface layer of snow through which absorption of solar radiation occurs is determined from measurements of intensities of visible radiation within the snow. Albedo values for the snow are computed from measurements of incoming and reflected solar radiation over the snow surface. The snow albedo is found to vary with solar altitude and cloudiness as well as with changes in physical characteristics of the snow. When long-wave radiation is considered along with solar radiation, it is found that during the ablation season, the diurnal net transfer of radiant energy to the melting snowpack is often greater when skies are overcast than when skies are clear. A comparison is made between the radiative energy transfer at the surface of a model glacier in the Juneau Ice Field, and a model glacier in the Alps.

It is shown that energy transfer to the snow by rain falling on an isothermal melting snowpack is an insignificant part of the total energy transfer.

From measured and calculated values of net energy transfer at the snow surface, energy transfer by radiation, and energy transfer by rain, values of energy transfer by turbulence are determined for a series of selected observation periods. These values are used to calculate exchange coefficients. It is shown that by making a slight modification in the functional expression for heat transfer by turbulence from that used by Sverdrup and Wallén, it is possible to obtain a nearly invariant relationship between the heat transfer by turbulence, windspeed, and the vertical temperature distribution above the surface when an inversion is present.

It is found that turbulent transfer of heat is the most important factor in causing ablation on the Lemon Creek Glacier. This turbulent transfer of energy becomes very large during summer storm periods. As a result, the number of warm storms passing over the glacier in a single ablation season can largely determine whether the glacier will end the season with a positive or negative mass budget.

INTRODUCTION

Studies of basic relationships between energy transfer processes and the energy exchange at a glacier surface are very few. *Wallén* [1948] presents a brief account of earlier papers on the subject. The studies of *Sverdrup* [1935, 1936 ab] on Isachsen's Plateau and the Fourteenth of July Glacier represent the classic investigations in this field, and the theory of heat exchange at a snow surface as developed by Sverdrup has been but slightly advanced since that time. *Wallén's* [1948] study on the Kårsa Glacier was a conscientious and enlightening piece of work, but unfortunately suffered from lack of sufficient instrumentation. More recently, valuable basic work on surface energy exchange has been carried out on glaciers in the Alps by *Hoinkes* [1952, 1953].

The major problem encountered in treatment of net surface energy exchange is determination of energy transfer by turbulence, because at the present time this term cannot be measured directly, and no reliable means has been demonstrated by which the term can be calculated from measurements of average wind, temperature, and humidity distribution over the snow surface.

From his field measurements on Isachsen's Plateau, Sverdrup established an empirical relationship between turbulent transfer of energy and wind, temperature, and humidity distribution near a snow surface. The empirical relationships were based on an average of many individual results from different observation periods. Deviations of individual Austausch coefficients computed for each observation period from average coefficients given by the empirical function were in many cases very large. Wallén likewise computed Austausch coefficients for several observation periods on the Kårsa Glacier and used them to obtain an average function for turbulent transfer of heat. Again, the deviations of individual

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coefficients from coefficients given by the average function were significant. Clearly, if the scatter of individual coefficients about an average curve is a result only of randomly distributed observation errors, the empirically derived expressions for Austausch coefficients should be valid and can be used to predict energy transfer by turbulence for any given distribution of wind, temperature, and humidity near the snow surface as has been tried by *Ahlmann* and *Thorarinsson* [1938], *Eriksson* [1942], *Light* [1941, 1943], and *Orvig* [1954]. On the other hand, in view of the lack of basic knowledge of atmospheric turbulence, it would seem there was at least an equal, if not greater possibility that the scatter of Austausch coefficients computed both by Sverdrup and Wallén was predominantly a result of a basic deficiency in the turbulence theory which led them in the first place to express turbulent transfer of energy through use of an exchange coefficient.

Wallén himself concluded, after comparing his results with those obtained earlier by Sverdrup; "My data . . . have also shown that it is not reasonable to apply Sverdrup's results to other glaciers, without a study of the laws governing exchange of momentum and heat in every particular case." Wallén's conclusion that laws governing exchange of momentum and heat as determined by Sverdrup were not universal clearly indicates that the empirical investigation of energy transfer by turbulence over snow is far from complete.

The purpose of the present study has been to perform a new empirical investigation of energy transfer at an isothermal melting snow surface, and its relationship to observed meteorological parameters, taking advantage of more refined instrumentation and methods of observation than had been available to Sverdrup and Wallén.

The specific objectives of the investigation have been:

(1) To determine the relationship of the net radiative energy exchange at the snow surface to atmospheric parameters and physical properties of the snow.

(2) To determine the practicability of using an exchange coefficient to relate turbulent transfer of energy to the observed wind, temperature, and humidity distribution near the surface.

(3) As part of a glaciological program on Lemon Creek Glacier, to determine the role of individual processes of energy exchange to ablation on the glacier.

Lemon Creek Glacier is located on the south side of the Juneau Ice Field, four airline miles from the city of Juneau, Alaska. The glacier is approximately four miles long, covers an area of some four square miles, and lies between 4500 and 2000 ft above sea level. The glacier is thermally temperate, and its climate is highly maritime. (A thermally temperate glacier is one in which the pressure-melting temperature of the ice is attained throughout the glacier during the ablation season.) Summer air temperatures over the glacier rarely fall below freezing. Data used in the present study were collected during the summers of 1953 and 1954 at a micrometeorological station on the glacier in the middle of an extensive, nearly level névé field at 4000 ft above sea level.

Equation for Surface Energy Exchange

In terms of individual transfer processes, an equation for energy exchange at a melting snow surface can be written as follows

$$F_a = I_h{}^{\downarrow}(1-\beta) + R_h{}^{\downarrow} - \sigma T_h{}^4 + Q_a + L_v f + c_w P_w (T_w - T_h) \quad (1)$$

Symbols used in the equation have the following meanings:

F_a Net energy exchange at the snow surface, gm cal $cm^{-2}min^{-1}$ (positive when there is a net transfer of energy to the snow.)

$I_h{}^{\downarrow}$ Insolation received at the snow surface, gm cal $cm^{-2}min^{-1}$.

β Albedo of the snow.

$R_h{}^{\downarrow}$ Long-wave back radiation received at the snow surface from clouds and atmospheric water vapor and carbon dioxide.

Q_a Heat transfer by conduction between the snow and atmosphere (positive when there is a net transfer of energy to the snow)

L_v Latent heat of vaporization.

f Rate of net condensation (positive) or net evaporation (negative) of water at the snow surface, gm $cm^{-2}min^{-1}$.

c_w Specific heat of water.

T_h Temperature of the snow surface °K.

T_w Temperature of rain falling on the snow surface, °K.

P_w Rate of precipitation of rain, gm $cm^{-2}min^{-1}$ (equivalent to the common usage of cm min^{-1}).

The investigation of terms in (1) will be treated in four stages in the following discussion: (a) determination of the net surface energy exchange, F_a, from field observations; (b) measurement and calculation of radiation terms; (c) calculation of the precipitation term; and (d) using results from parts (a), (b), and (c), calculation of the terms

$Q_a + L_v f$ and correlation of these terms with the observed wind, temperature, and humidity distribution in the air layers near the snow surface.

Determination of Net Surface Energy Exchange

Within isothermal, melting snow there is no heat transfer by conduction, and the net energy exchange between the snow pack and its environment is represented by the rate of melt of the snow multiplied by the heat of fusion. In the present case where the snow is deep and overlies ice, also isothermal at the melting point, no heat is received in the snowpack from below and melting of the snow results solely from a positive net energy exchange at the snow-atmosphere interface.

An accurate determination of rate of melt in the snow is therefore basic to calculation of the energy exchange between the snow and atmosphere during the ablation season. In earlier literature, there appears to be considerable confusion concerning the relationship between melting and ablation in a glacier. Methods of measuring either term have been based upon assumptions which are inadequate. First, it must clearly be recognized that melting of snow, ice, or firn in a glacier is not a process of ablation. Ablation is the loss of mass from a glacier; melting, on the other hand, is the change of mass from a solid to a liquid state. In geological terms, melting is a process of weathering, while ablation is an erosion process. The two processes are related in that melting makes water available for ablation in the form of runoff from the glacier. On the other hand, all the water released by melting does not necessarily take part in the runoff.

Further difficulty arises when the rate of lowering of a snow surface as measured, for example, with 'ablation stakes,' is taken as a measure of either ablation or rate of melt. The rate of lowering of a snow surface is essentially a measure of the decrease in volume of the snowpack, and is representative of the rate of ablation only if density of the snow is constant in time and space. Measurements of surface ablation of snow on Lemon Creek Glacier by *La Chapelle* [1954] have shown that at least over short periods of time, the rate of lowering of the snow surface is not indicative of the rate of ablation. It has been shown in an earlier paper [*Hubley*, 1954] that in a vertical column of unit cross-sectional area extending from the base of the snowpack, $z = 0$, to the upper surface, $z = h$, the rate of melt, dm_i/dt, can be expressed by

$$dm_i/dt = dm/dt - (\rho_w')_h \, \partial h/\partial t - \int_0^h \frac{\partial \rho_w'}{\partial t} \, dz \qquad (2)$$

In this equation, m_i is the total mass of solid ice in the vertical column, m is the total mass of water and ice in the column, and ρ_w' is the mass of liquid water per unit volume of snow.

On Lemon Creek Glacier the term, dm/dt, was measured by observing the change in weight during an observation period of a vertical column of snow. A detailed description of the procedure is given by *La Chapelle* [1954].

No instrumentation was available to measure the terms

$$(\rho_w')_h \, \partial h/\partial t + \int_0^h \frac{\partial \rho_w'}{\partial t} \, dz$$

however for observation periods during which the percentage of free water in the snow remains constant, the relative water content is introduced where

$$\alpha = \rho_w'/\rho' \; ; \qquad \rho' = m/h$$

and (2) reduces to

$$dm_i/dt = (1 - \alpha) \, dm/dt \qquad (3)$$

It was found that the assumption of a constant ratio α held quite well much of the time during the summer season, except during periods when winds were very light and clear weather prevailed. In the latter case, values of α apparently followed a strong diurnal variation which lagged several hours behind the diurnal variation in the net radiational exchange. During other periods when skies were overcast and windspeeds were moderate or strong, values of α were determined from calorimeter measurements, that is, of the drop in temperature experienced by a known quantity of hot water in the calorimeter when a known mass of snow was introduced. Values of α were found during these periods to remain in the range .07 to .10.

The Radiational Energy Exchange

Instrumentation—Two ten-junction Eppley pyrheliometers were mounted four feet above the snow surface, one upright to measure incoming, and one inverted to measure reflected insolation. Outputs from the pyrheliometers were fed into Leeds and Northrup Speedomax which automatically recorded a set of readings once every 24 sec.

Recent laboratory tests on the Eppley pyrheliometer have revealed instrumental errors [*MacDonald*, 1951; *Fuquay* and *Buettner*, 1956] which indicate that the Eppley is, in its present state,

unsatisfactory for very refined radiation measurements, particularly at high latitudes. The most serious error in the instrument, and most difficult for which to correct is a dependence of the instrument response on angle of incidence of radiation falling on the sensing element. Values recorded by the Eppley and used in this paper have been corrected for these errors. For detailed calculations of the energy exchange, no pyrheliometer data has been used for clear periods when the Sun's elevation above the horizon was less than 30°, as the cosine response error becomes so great under these conditions that reliability of corrected values is questionable.

A Beckman and Whitley net radiometer was used to measure net long- and short-wave radiation at a horizontal plane near the snow surface. These values were also recorded on the Speedomax. For observations under all weather conditions, this method for measuring net radiation leaves much to be desired because the radiometer will not operate correctly if any water is on the exposed radiometer plates, which means the measurements are invalid during periods of fog or precipitation. An added difficulty in use of the radiometer occurred during periods of sunshine when a visible change with time in the nature of the snow surface directly under and around the instrument took place, apparently as a result of intensified melting by radiation from the radiometer plates to the snow. This led to an albedo of the snow under the radiometer which was different from that of the surrounding unobstructed snow surface, and the radiometer values could not be taken as representative of the radiation balance over free, undisturbed snow. The problem is not completely solved by mounting the instrument some distance above the snow surface, for radiation from the air layers between the instrument and the snow is then great enough to give measured values of net radiation significantly different from those at the snow surface. Radiometer values were considered valid during cloudy daytime periods when no appreciable fog nor precipitation occurred, and during clear or cloudy nighttime periods without precipitation or fog.

A few measurements were made of penetration of insolation into the snow. Instrument used was a very small, tubular pyranometer designed specifically for these observations by K. J. K. Buettner. The pyranometer, an experimental model, contained a thermopile which operated on the same principle as the Eppley. The instrument was approximately five cm long by one cm in diameter, and could easily be inserted in a small hole in the snow for radiation measurements. The special pyranometer could not be used for measurements of directional radiation because of the tubular shape of the glass case, but it was successfully used for relative measurements of radiation intensity in the snow where the incident radiation on the instrument was very nearly 100 pct diffuse. At several depths in the snow, readings were made of radiation reaching the instrument both from above and below.

Short-wave radiation.—Of an amount, $I_h{}^{\downarrow}$, of insolation reaching the snow surface, an amount, $r_h I_h{}^{\downarrow}$, is reflected at the surface and never enters the snow. An amount, $I_h{}^{\downarrow}(1 - r_h)$ enters the snow where scattering, reflection, and absorption take place. Of the amount entering the snow, a quantity, $I_h{}^{\downarrow}(1 - \beta)$, where β is albedo, is absorbed by the snow and the remainder, $I_h{}^{\uparrow}$, is internally reflected and scattered out of the snow. Of the processes by which heat is transferred from the meteorological environment to isothermal, melting snow, insolation is the only one in which the heat transfer takes place through a layer of snow of significant thickness. An estimate of the depth to which absorption took place during the present study comes as a result of the solar radiation penetration study described next.

Penetration and absorption of short-wave radiation in the snow—Dunkle and *Gier* [1953] have performed a theoretical analysis of radiation within a diffusing medium based on the assumptions: (a) The medium is composed of a perfectly diffusing material with a uniform distributed reflectivity. (b) The absorption coefficient k is uniform throughout the medium. (c) Emission within the medium is negligible, that is, the temperature is low compared to that of the energy source.

For a deep snow cover, Dunkle and Gier obtain solutions of the form

$$I_z{}^{\downarrow} = A(1 - r_h)I_h{}^{\downarrow}e^{-\gamma z};$$

$$I_z{}^{\uparrow} = B(1 - r_h)I_h{}^{\downarrow}e^{-\gamma z} \quad (4)$$

where A, B, γ, and r_h (surface reflectivity), are constants; $I_z{}^{\downarrow}$ and $I_z{}^{\uparrow}$ are respectively the downward directed and upward directed intensities of radiation at depth z in the snow. An obvious result of these equations is that the ratio $I_z{}^{\uparrow}/I_z{}^{\downarrow}$ is constant with depth. In Table 1 are shown relative intensities of short-wave radiation in the snowpack as measured on Lemon Creek Glacier, with values of the above ratio for each depth. The large difference between the ratio at 7.6 cm and those at greater depths indicates that the absorp-

TABLE 1 – *Measured intensities of short-wave radiation in the snowpack*

Depth	$I_z^{\downarrow}$	$I_z^{\uparrow}$	$I_z^{\uparrow}/I_z^{\downarrow}$
cm			
7.6	17.5	9.2	0.53
15.2	8.4	8.0	0.95
30.5	4.4	4.2	0.95
58.5	2.8	2.8	1.00

Values of $I_z^{\downarrow}$ and $I_z^{\uparrow}$ relative to $I_h^{\downarrow} = 100$.

tion and reflection coefficients are not uniform within the first several centimeters of snow below the surface.

Visual observations showed that visible light in the snow very rapidly becomes blue with depth. This change in spectrum of penetrating radiation with depth demonstrates that the absorption and reflection coefficients in the snow are functions of radiation wave length. Eq. (4) might be found to hold for absorption and reflection by snow of monochromatic radiation, but in the present case where nearly the full spectrum of insolation is considered, the equations must take the form

$$I_z^{\downarrow} = \int_{\lambda} A_{\lambda}(1 - r_h)_{\lambda}(I_h^{\downarrow})_{\lambda} e^{-\gamma_{\lambda} z}\, d\lambda;$$

$$I_z^{\uparrow} = \int_{\lambda} B_{\lambda}(1 - r_h)_{\lambda}(I_h^{\downarrow})_{\lambda} e^{-\gamma_{\lambda} z}\, d\lambda \quad (5)$$

where λ is wave length, $(I_h^{\downarrow})_{\lambda} d\lambda$ is the intensity of incoming radiation in the wave length band between λ and $\lambda + d\lambda$, and the integrals are taken over the complete spectrum of solar radiation incident at the snow surface.

Approximate functions were fitted to the observed data by assuming that the penetrating radiation could be considered in two parts; one part (blue light), for which absorption by snow was very low, and the other part (minus blue light), for which absorption by snow was high. It was assumed the minus blue light was a negligible part of the spectrum of penetrating radiation at the 30.5- and 58.5-cm depths, and data from these two depths were fitted by the curves

$$\frac{100(I_z^{\downarrow})_{\text{blue}}}{I_h^{\downarrow}} = 7.2e^{-0.016z};$$

$$\frac{100(I_z^{\uparrow})_{\text{blue}}}{I_h^{\downarrow}} = 6.5e^{-0.014z} \quad (6)$$

From the above expressions, theoretical intensities of blue light were calculated for the 7.6 and 15.2 cm depths, and subtracted from the observed intensities at these depths. The differences were taken to be the intensities of minus blue light, and were fitted by the curves

$$\frac{100(I_z^{\downarrow})_{\text{minus-blue}}}{I_h^{\downarrow}} = 45e^{-0.185z};$$

$$\frac{100(I_z^{\uparrow})_{\text{minus-blue}}}{I_h^{\downarrow}} = 4.3e^{-0.030z} \quad (7)$$

Equations (7) for minus blue light can be valid only between the surface and 15 cm depth, for below 15 cm, these equations give larger values for upward directed radiation than for downward directed radiation. On the same basis, (6) for blue light can be valid only between the surface and 60 cm depth. The crossing of the curves is an unavoidable result of different exponents between the downward and upward directed radiation intensity curves for blue light in (6), and for minus blue light in (7). The fact that the exponents in (6) are very nearly the same indicates that the spectra of downward directed and upward directed radiation at the 30.5- and 58.5-cm depths were also nearly the same. The pronounced difference between exponents in (7) show that the spectra of downward directed and upward directed radiation at the 7.6 and 15.2 depths were quite different, even after the estimated blue-light intensities at these depths were subtracted. If it were possible to break down the wave lengths in integrals (5) into more than two bands for the purpose of fitting curves to the measured data, it should be found that the larger the number of bands used, and therefore the narrower each finite band of wave lengths to which approximation curves of the form (6) and (7) are fitted, the more nearly the exponents for downward and upward directed radiation in each band will approach a common value.

Of principal interest, on the other hand, is an estimate of how well the fitted curves (6) and (7) may approximate intensities of radiation within the layer of snow between 7.6-cm depth and the surface, where satisfactory measurements of radiation intensity could not be made with available instruments. A partial check on the fit is given by calculating the snow albedo from equations (6) and (7) and comparing the result with the albedo computed from pyrheliometer measurements. The accuracy of the albedo so calculated will depend entirely on how accurately the fitted curves estimate the intensity of radiation penetrating the snow surface and intensity of radiation being reflected and scattered out of the snow at the surface.

TABLE 2 – *Absorption of solar radiation in the snowpack*

Upper and lower boundaries of layer (depth)	Radiation absorbed in layer as per cent of total radiation absorbed in all layers
cm	
0–1	19
0–2	33
0–3	45
0–4	57
0–5	64
0–7.6	80
0–15.2	99

From the fitted curves the albedo will be given by

$$\beta = \frac{I_h{}^{\downarrow} - (I_0{}^{\downarrow})_{\text{blue}} - (I_0{}^{\downarrow})_{\text{minus-blue}} + (I_0{}^{\uparrow})_{\text{blue}} + (I_0{}^{\uparrow})_{\text{minus-blue}}}{I_h{}^{\downarrow}} \quad (8)$$

From (6) and (7) the calculated value of β is found to be 0.587. At the time radiation penetration measurements were made, the snow albedo computed from pyrheliometer measurements was 0.64. Agreement between the two albedo values appears to be fairly good considering all possible errors that may enter, both in measurements and in approximations used in calculating radiation intensities in the snow.

Eq. (6) and (7) have been used to calculate the ratio of absorbed radiation within selected layers of snow between the surface and 7-cm depth, to total radiation absorbed by the snowpack. These values are shown in Table 2 together with ratios computed from data in Table 1 for layers of greater than 7-cm thickness.

Albedo—Albedo measurements made by *Olsson* [1936], *Prohaska* and *Thams* [1940], and *Sauberer* and *Dirmhirn* [1951] have indicated that under some conditions snow albedo varies with cloudiness and with solar altitude. These are factors which are not often considered in treatments of the effect of albedo on the surface energy exchange.

Snow albedos on Lemon Creek Glacier during the summer were found to have a very decided dependence on solar altitude and cloudiness. An account of these albedo measurements has been published [*Hubley*, 1955]. Subsequent correction of incoming and reflected radiation values measured with the pyrheliometers following laboratory research into errors of the instruments have given lower albedo values for low solar angles from those originally published. Although the reliability of corrected values of incoming and reflected solar radiation taken from pyrheliometer measurements decreases rapidly at low solar angles, albedos computed from the corrected pyrheliometer readings for low solar altitudes are believed to be more reliable for the following reason: Visual observation showed that reflection from the snow at low solar altitudes was, to a considerable extent, specular. Because that portion of the reflected solar radiation which was specular intercepted the inverted pyrheliometer at very nearly the same angle of incidence as incoming radiation striking the upward directed pyrheliometer, errors in cosine response of the two instruments partially cancelled in computations of ratios of reflected to incoming values of radiation as measured by the instruments.

Albedos over the snow were found to increase as the solar altitude decreased. On clear days, the average ratio of the albedo near sunrise and sunset to the albedo during the midday was 1.23. On days with overcast skies but no fog, the average ratio of midday albedos to midday albedos on clear days was 1.15. With the presence of fog in addition to an overcast, the average ratio of midday albedos to midday albedos under clear conditions was 1.25. In Figure 1 are shown average values of albedo at ten-degree intervals of solar altitude for four clear days on which observations were made, together with representative albedos on overcast days with and without fog. On all four clear days, the snow surface was frozen during early morning hours when albedos were highest.

These diurnal variations in snow albedo are a result primarily of the presence of large ice granules making up the metamorphosed summer snowpack. These granules produce considerable specular re-

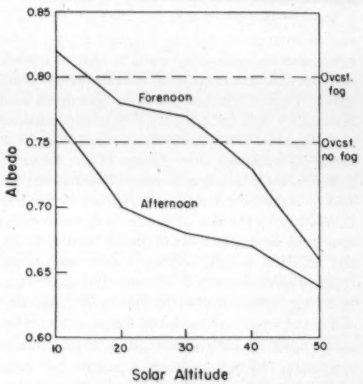

FIG. 1 – Average albedo values measured over snow on clear days (solid lines), and on overcast days (dashed lines)

flection which, at the snow surface, increases with increasing angle of incidence. In contrast, *Eckel* and *Thams* [1939] found no diurnal variation in albedo over winter snow which is composed of very fine crystals and consequently produces little or no specular reflection.

In the present case, diurnal changes in physical characteristics of the snow surface play a secondary, but also significant role in causing albedo fluctuations. These effects have been discussed in more detail in an earlier paper [*Hubley*, 1955].

There is great need for more detailed investigation of glacier albedos. The use of a constant mean albedo value in computing the surface energy exchange has clearly been shown by recent work to be inadequate. *Sauberer* and *Dirmhirn* [1951] have pointed out that albedo fluctuations not only can influence the magnitude of the net radiation exchange, but frequently as well reverse sign; a positive net exchange becoming negative, or vice versa.

Long-wave radiation—In studies of surface energy exchange over snow, long-wave radiation exchange between clouds, atmosphere, and the surface has been one of the least understood, yet is one of the most important processes of heat exchange. Sverdrup used an empirical equation to estimate the net long-wave radiation over snow, which under all conditions gave a negative net long-wave radiation exchange (heat lost from the surface). Wallén also used an empirical equation which led always to negative values of net long-wave radiation exchange at the snow surface.

More than thirty years ago, *Defant* [1922], concluded that the long-wave radiation from a cloud cover was approximately equal to that of a black body at the temperature of the base of the cloud cover. This conclusion has been shown to hold reasonably well by *Hoinkes* [1951], and *Sauberer* and *Dirmhirn* [1951] from direct measurements of radiation exchange over glaciers in the Alps. To this writer's knowledge, however, Hoinkes was the first to have indicated the significance of this fact in relation to the sign of the net long-wave radiation term over a temperate glacier, where, during the ablation season, overcasts exist with cloud temperatures above 0°C. Because the glacier surface temperature cannot rise above 0°C, the sign of the net long-wave radiation flux in this case becomes positive. With an overcast of thick cumulus congestus, Hoinkes measured a positive net long-wave radiation of 0.033 gm cal $cm^{-2}min^{-1}$, corresponding to radiation from clouds and atmosphere at a black body temperature of 5°C.

During the 1954 field season on the Lemon Creek Glacier, attempts were made to obtain careful measurements of the net radiation balance over the snow at night when a complete overcast was present. This proved to be a nearly impossible feat, as overcasts were invariably accompanied by precipitation or dense fog which wetted the radiometer plates and made the instrument readings useless. On two different nights, readings were obtained for approximately ten minutes each between the time of formation of complete overcast conditions, and the beginning of precipitation.

In the first case, a net radiation of -0.0053 gm cal $cm^{-2}min^{-1}$ was measured at night under an overcast of strato-cumulus with cloud bases at an elevation of approximately 1000 ft above the glacier surface. Assuming the snow emissivity was that of a black body, back-radiation in this case corresponded to black body radiation at a temperature of approximately -0.8°C. Shortly after the readings were made, precipitation commenced in the form of mixed rain and snow. It is concluded therefore that the cloud temperature was actually at or very slightly below 0°C.

In the second case, a net radiation of $+0.0227$ gm cal $cm^{-2}min^{-1}$ was measured at night under a dense cloud layer approximately 100 ft above the glacier surface. Again, assuming emission from the snow was that of a black body, the above value of net radiation would indicate the snow received back radiation from the clouds and intervening air layers equivalent to that of a black body having a temperature of +3.3°C.

On Lemon Creek Glacier where temperatures remain above freezing with few exceptions throughout the summer season, very dense, low-lying clouds are frequent with cloud temperatures ranging from 0°C to as much as 12°C. For this reason, the long-wave radiation balance is not only positive very often during the ablation season, but can be a major contributing factor to melting of ice and snow on the glacier. During the month of August 1953, a very warm and cloudy month on the glacier, sky cover over the glacier averaged nine-tenths, with an average cloud temperature estimated at 5°C. Assuming the cloud-cover radiated as a black body, sufficient heat was supplied to the glacier by net long-wave radiation during this month to melt approximately 15 cm of ice; approximately ten per cent of the total melt measured that month at the micrometeorological station on the glacier.

To determine the net long-wave radiation balance at the snow surface under completely clear

conditions, back radiation from water vapor and carbon dioxide was computed from the following equation for long-wave radiation received at a horizontal surface of infinite extent [*Fleagle* and *Badgley*, 1951]

$$R_h{}^{\downarrow} = \sum_{n=1}^{\infty} \sigma T_n{}^4(\overline{\partial\epsilon}/\partial w)_n(\Delta w)_n + 0.18\sigma T_h{}^4 \quad (9)$$

where the T_n are mean temperatures within successive horizontal layers of the atmosphere, ϵ is the emissivity of water vapor, w the optical path length of water vapor, and Δw the increment of the optical path length contained within a particular layer. The second term on the right is an approximate correction for back radiation from carbon dioxide in the atmosphere.

On the basis that the snow radiates as a black body, the effective long-wave radiation R_e is given by

$$R_e = \sum_{n=1}^{\infty} \sigma T_n{}^4(\overline{\partial\epsilon}/\partial w)_n(\Delta w)_n - 0.82\sigma T_h{}^4 \quad (10)$$

The contributions of back radiation from air layers near the glacier surface were computed using air temperatures measured at various heights from the surface to seven meters above the surface, and humidities determined from psychrometer measurements. The assumption was made that the mean temperature of a horizontal layer bounded by two successive levels at which temperatures were measured was equal to the arithmetic mean of the two measured values.

To compute the radiation contribution from air layers above seven meters, upper air temperature and humidity data over the Juneau area were estimated from radiosonde data taken at Yakutat, 240 mi northwest from Juneau, Annette Island, 240 mi southwest, and Whitehorse, 175 mi north from Juneau. Data from these stations appeared to allow reasonable estimate of upper air temperatures over Juneau provided no fronts lay between Juneau and any of the stations used.

On three clear nights during the 1954 season, measurements of the effective long-wave radiation were obtained with the radiometer and compared to values computed from (10). Results are shown in Table 3. In the first case, the measured value of R_e was greater than the theoretical value by nine pct; in the second case by four pct; and in the third case by one pct.

Occasionally under apparently clear night skies, the effective radiation had a large negative value during the early part of the night, then sharply changed to a value near zero later in the night. No measurable change of the snow temperature from 0°C was found at these times, therefore the measurements indicated a sudden increase in back radiation, even though no clouds were visible. A similar phenomenon has earlier been reported by *Robinson* [1947].

In the absence of radiosonde data from the immediate area, it is not possible to substantiate a cause for this phenomenon. Of significance, on the other hand, is that these measurements show that visual observations alone cannot indicate whether or not back radiation from the atmosphere as calculated from (10) is appropriate in any given case when clouds are not present.

Theoretical treatment of long-wave back radiation at the snow surface for periods when the sky is only partially obscured by clouds requires a combination of the theoretical treatments of back radiation under completely clear and completely overcast skies. The effect of clouds on back radiation received at the surface is a function of cloud height, cloud temperature, per cent of cloud cover, and, below some critical value, on cloud thickness. Because of observational difficulties in measuring these factors in the field, Sverdrup, Wallén, Sauberer and Dirmhirn, and Hoinkes have used empirical formulas to express back radiation as a function only of per cent of sky cover by clouds, and back radiation under clear conditions.

If again it is assumed that the clouds are emitting radiation equivalent to that of a black body at the temperature of the cloud base, and that the radiation from the air layers between the cloud bases and the surface is negligible, then the back radiation can be expressed by

$$R_h{}^{\downarrow} = \sigma b_c T_c{}^4 + (1 - b_c) \cdot \left[\sum_{n=1}^{\infty} \sigma T_n{}^4(\overline{\partial\epsilon}/\partial w)_n(\Delta w)_n + 0.18\sigma T_h{}^4\right] \quad (11)$$

where b_c is the fraction of the sky hemisphere covered by clouds, and T_c is the temperature of the cloud bases. The validity of equation (11) must decrease as the height of the cloud bases increase, for then radiation from intervening air layers becomes increasingly significant.

In Figure 2 is shown the effect of cloud temperature and per cent of sky cover on back radiation

TABLE 3 – *Net long-wave radiation at snow surface*

Date	Measured	Calculated
July 10, 1954	−0.0978	−0.1074
July 27, 1954	−0.0766	−0.0798
June 8, 1954	−0.1086	−0.1096

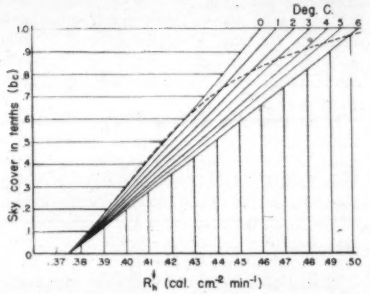

FIG. 2 – Long-wave radiation received from clouds at the snow surface as a function of pct of sky cover and cloud temperature. Solid lines are computed from Eq. (11); dashed lines from Eq. (13)

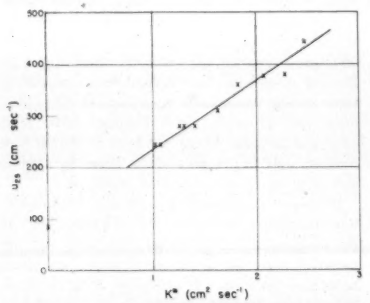

FIG. 3 – Values of the exchange coefficient K_z^* computed from data collected on Lemon Creek Glacier

under low clouds as computed from equation (11), with the back radiation for a clear sky taken as 0.374 gm cal $cm^{-2}min^{-1}$.

Sauberer [1951] has calculated back radiation for varying degrees of cloudiness from the empirical equation

$$R_h{}^{\downarrow} = R'^{\downarrow}(1 + kb_c) \qquad (12)$$

where $R'^{\downarrow}$ is back radiation when $b_c = 0$, and k is taken to be a constant. A comparison of this equation with (11) shows they are identical if, instead of k being a constant,

$$k = (\sigma T_c{}^4 - R'^{\downarrow})/R'^{\downarrow}$$

From radiation measurements in the Alps, *Sauberer* and *Dirmhirn* [1951] found values of k in the range 0.29 to 0.34. With $R'^{\downarrow} = 0.374$, a plot of (12) with $k = 0.29$ coincides with the line for 4°C, and with $k = 0.34$, coincides with the line for 6°C in Figure 3. In later studies, *Sauberer* and *Dirmhirn* [1952] expressed the back radiation by the simple form

$$R_h{}^{\downarrow} = \omega R'^{\downarrow} \qquad (13)$$

where ω is a 'cloudiness factor.' Using mean values for ω for each fractional degree of sky cover in tenths as found by Sauberer and Dirmhirn, a plot of (13) is shown by the dashed curve in Figure 2. Shape of the curve may reflect a correlation between degree of cloudiness and mean cloud height and cloud temperature. Comparison of curves leads to the conclusion that there is no satisfactory method at present for estimating back radiation when skies are partly cloudy, in the absence of direct radiation measurements.

Role of radiation in energy exchange on the glacier during the ablation season—The greatest number of hours of clear weather in the Juneau Ice Field occur usually during the months of May, June, and July. Because these are also the months during which days are longest and solar angles highest, appreciable insolation arrives at the surface during this period. On June 8, 1954, a clear day throughout, the total insolation measured at a horizontal surface on the glacier was 822 gm cal cm^{-2}. Although no measurements could be obtained for a clear day in August, it is estimated that the insolation with clear skies on August 8 would be very nearly 700 gm cal cm^{-2} day^{-1}. By September 8, the daily insolation with clear skies should be in the order of 490 gm cal cm^{-2}. Although the clearest weather during the year occurs during the period of maximum possible insolation, solar radiation is not particularly effective in producing melt early in the summer. During May, June, and early July, the glacier is almost completely snow covered, and therefore presents a surface of much higher albedo than it does late in the season when considerable bare ice may be exposed below the firn limit. Taking a mean albedo of summer snow for the Lemon Creek Glacier as 0.70, and of glacier ice as 0.45, Table 4 demonstrates the amount of solar

TABLE 4 – *Quantity of solar radiation absorbed on a clear day by snow and glacier ice for representative values of insolation in June, August, and September, and representative albedos in the Juneau Ice Field*

$I_h^{\downarrow}$	Snow	Ice
822	247	452
700	210	385
490	147	270

radiation which would be absorbed by horizontal surfaces of snow and ice respectively on a clear day.

Because of albedo effects, the amount of solar radiation absorbed by a bare ice surface in early September may be greater than the absorption by a snow covered glacier surface in June. It appears therefore that on the lower parts of the glacier, solar radiation on clear days will play a more important role in glacier melt late in the ablation season when the glacier surface is free of snow, than early in the season when the glacier is as yet snow covered, although the total daily insolation will be appreciably less late in the season. It is of interest to digress for a moment from the Juneau Ice Field for a more striking example of this albedo effect.

At an elevation of 3000 m in the Alps, *Sauberer* and *Dirmhirn* [1950] have determined values of daily insolation received at a horizontal surface with clear skies on the 15th of each month. In the same paper, they quote albedos applicable to parts of the Alps of 0.8 for fresh snow, 0.6 for old snow, 0.5 for watery old snow, and 0.33 to 0.20 for glacier ice. Using these values for a guide, a model can be postulated in the Alps of a glacier which is completely snow covered on June 15, $\frac{3}{4}$ snow covered and $\frac{1}{4}$ exposed ice on July 15, and on August 15, $\frac{1}{2}$ snow covered, and $\frac{1}{2}$ exposed ice. The average daily amounts of solar radiation absorbed at the glacier surface on these three dates under clear skies as calculated for the model are given in Table 5.

The effect of cloudiness on short-wave radiation received at the glacier surface has been discussed by *Sauberer* and *Dirmhirn* [1950]. For the month of June they find the daily insolation received at a horizontal surface under overcast skies is 60 pct of that received under clear skies. The same percentage relationship was found from measurements on Lemon Creek Glacier. On the other hand, because snow albedo on Lemon Creek Galcier increased with increasing cloudiness, it was found that the absorbed insolation on an overcast day was only 50 pct of that absorbed on a clear day.

When long-wave radiation is considered along with the short-wave, the effect of cloudiness on total radiation absorbed by the snow may be opposite to that usually observed over other surfaces. On a clear day in June, insolation absorbed at the micrometeorological station site is approximately 247 gm cal cm^{-2}. At the same time, loss by long-wave radiation is in the order of 122 gm cal cm^{-2}, leading to a net radiation gain of 125 gm cal cm^{-2} day^{-1}. With total overcast and cloud temperatures at 0°C, the net long-wave radiation exchange is virtually zero, so that the net total radiation exchange is approximately the same as that for a clear day. For cloud temperatures of 5°C, the net long-wave radiation gain will be in the order of 50 gm cal cm^{-2}day^{-1}. The net total radiation gain then becomes 174 gm cal cm^{-2}day^{-1}, or nearly 40 pct greater than that on a clear day.

From this discussion it is possible to state some general conclusions concerning the radiation exchange at glacier surfaces during the ablation season:

(1) The earlier in the season the firn limit retreats up-glacier, and the more rapidly this retreat takes place, the greater will be the net radiative transfer of heat to the glacier during the season. This effect will be minimized on most Juneau Ice Field glaciers which have relatively clean ice with high albedo, and maximized on many glaciers in the Alps where glacier ice has low albedo due to large amounts of impurities in the ice.

(2) A surface having an albedo above a certain critical value will absorb more radiation under overcast skies than under clear skies, whereas a surface having an albedo less than this critical value will experience a greater absorption of radiation with clear skies than with cloudy skies. This critical albedo will vary directly with the daily amount of solar radiation falling on the surface under clear conditions, and inversely with cloud temperature. Table 6 gives calculated values of this critical albedo for Lemon Creek Glacier using the assumptions: (a) Insolation received when an overcast is present is 60 pct of that received with clear skies; (b) mean albedo of the glacier surface with an overcast is 1.07 times the mean albedo with clear skies; (c) the diurnal net long-wave radiation balance under clear skies is -122 gm cal cm^{-2}, and for overcast skies is given by $\sigma(T_s^4 - T_h^4)$.

Comparison of these critical albedos with albedos measured on the glacier leads to the conclusion

TABLE 5 – *Mean diurnal absorption of solar radiation on horizontal surface of model glacier in the Alps*

Glacier surface	$I_h^{\downarrow}$		
	June 15 841	July 15 817	August 15 724
All snow covered, mean albedo 0.70 (snow, 0.70)	252	...	...
$\frac{3}{4}$ snow covered (snow, 0.60), $\frac{1}{4}$ bare ice (ice, 0.28), mean albedo 0.52	...	392	...
$\frac{1}{2}$ snow covered (snow, 0.50), $\frac{1}{2}$ bare ice (ice, 0.28), mean albedo 0.39	...	...	442

TABLE 6 – *Critical albedo values for various cloud temperatures and values of solar radiation which would be received at a horizontal surface if clouds were not present*

$I_h^{\downarrow}$ (clear)	Cloud temperature	
	0°C	5°C
cal cm^{-2} day^{-1}		
800	0.83	0.66
700	0.63	0.43
600	0.55	0.32
500	0.44	0.16

that, as long as air and cloud temperatures over the glacier remain above the freezing temperature during the ablation season, melting on the glacier caused by absorption of radiation will vary directly with the frequency of overcasts during the ablation season.

Energy Exchange by Rain

Regular daily measurements of rainfall were made at the camp site on a ridge west of the glacier using a standard rain gage. For time periods shorter than a day, amounts of rainfall at the micrometeorological station on the glacier were calculated from the weight of water collected in a flat, shallow pan set on the snow surface.

Energy transfer by rainfall at the snow surface is represented by

$$c_w(T_w - T_h)P_w$$

Heat transferred by rain to snow whose temperature is at the melting point is relatively insignificant in producing melting. With low clouds over the glacier producing rain having the same temperature as the cloud base, a rainfall rate of the order of ten cm per day would be required to transfer heat to the glacier at the same rate heat would be supplied by long-wave radiation alone.

August, 1953, was the wettest month on Lemon Creek Glacier during which observations were made. Total rainfall for the month was 46 cm. Using the estimated average cloud temperature of 5°C given earlier for that month as the appropriate average rain temperature, heat transfer by rain during the month was sufficient to melt only three cm of ice; approximately two pct of the total melt measured at the micrometeorological station.

This is not to say that rainfall is never an important factor in the energy exchange. Rain having a temperature of 0°C and falling on snow whose temperature is below freezing would freeze as it percolates through the snow and thereby transfer to the snow approximately 80 gm cal cm^{-2} for each cm of rain that fell. On the other hand, once the snow temperature was raised to the melting point, the rain would remain liquid as it passed through the snow cover, and no longer would serve to transfer heat to the snow.

Turbulent Transfer of Heat

Snow is a highly permeable substance, and for this reason convection and mechanical turbulence are not necessarily zero at a snow-atmosphere interface. There can, therefore, be turbulent transfer of heat at the snow surface.

Using *Montgomery's* [1948] derivations, the transfer of heat at the snow surface by turbulence may be expressed by

$$Q_a + L_v f = K_h \bar{\rho}_h (\partial \overline{Y}_t / \partial z)_h,$$

$$\overline{Y}_t = c_p(T_a - T_0) + L_v q + \phi \quad (14)$$

where K_h is the exchange coefficient at the surface, ρ_h is the mean air density at the surface, T_a is the air temperature, T_0 is an arbitrary absolute temperature at which enthalpy of dry air and saturated water or ice is taken to be zero, L_v is the latent heat of vaporization at T_0, q is the specific humidity, and ϕ is geopotential.

By restricting the discussion to the most common situation in which the sum of the terms $c_p\, \partial \overline{T}/\partial z$ and $L_v\, \partial q/\partial z$ is several orders of magnitude greater than the geopotential gradient very close to the snow surface, (14) can be reduced to

$$Q_a + L_v f = K_h \bar{\rho}_h [L_v (\partial \bar{q}/\partial z)_h + c_p (\partial \overline{T}_a/\partial z)_h] \quad (15)$$

The correct and complete analytical expressions for K are not known, and cannot be derived from any well established theory. There exist several hypotheses from which functions for K have been developed, [for example *Taylor*, 1915; *Sverdrup*, 1936a] however these functions include parameters which cannot be observed nor measured in order to test the individual hypotheses. "As yet, there is no generally accepted formulation of the problems of heat transfer by atmospheric turbulence." [*Sutton*, 1953].

Whether or not (15) is a useful or 'proper' expression for turbulent transfer between the atmosphere and the underlying surface can only be found by its empirical testing. If the coefficient K is found by experiment to behave in an orderly fashion as a function of measurable parameters such that its value may be accurately predicted for any real case, then the form (15) has definite value.

In attempting to solve (15) for the exchange coefficient, an immediate difficulty arises in that it is not possible by any present method to measure

even the proper order of magnitude of the temperature gradient at the surface. For this reason, it becomes necessary to consider the energy balance of an air layer of finite thickness adjacent to the snow surface in order to perform a calculation of K. The air layer is chosen arbitrarily as that between the surface, h, and $h + 1$ cm.

The assumptions are now made that: (1) The horizontal gradients of temperature and specific humidity are negligibly small compared to the vertical gradients near the snow surface. (2) The divergence of the energy transfer within the first centimeter of air above the snow surface is negligibly small in magnitude compared to that of the rate of energy transfer through the layer. On the basis of these assumptions, the energy balance of the layer would be

$$L_v + Q_a = K_{h+1}\bar{p}_{h+1}[L_v(\partial\bar{q}/\partial z)_{h+1} + c_p(\partial\bar{T}_a/\partial z)_{h+1}] \quad (16)$$

The specific humidity can be expressed in an approximate form by $q = \eta e/p$, where η is the ratio of the molecular weight of moist air to the molecular weight of dry air; e is vapor pressure, and p is total atmospheric pressure.

Using this approximation together with the hydrostatic equation, $\partial p/\partial z = -g\rho_a$, and the Clausius-Clapeyron equation in the form

$$de/dT_d = L_v e/R'T_d^2$$

it can be shown that

$$\partial q/\partial z = \eta e/p\left(\frac{L_v}{R'T_d^2}\frac{\partial T_d}{\partial z} + g\rho_a/p\right) \quad (17)$$

where R' is the gas constant for moist air, T_d is the dewpoint temperature in deg C, and g is gravitational acceleration.

Wet-bulb temperatures measured over the snow surface with an Assmann psychrometer were always found to be above 0°C. Further, measurements within a few centimeters of the snow surface with the psychrometer showed the relative humidity near the surface to always be very close to, or at 100 pct.

The added assumption is made therefore that the air was saturated at one cm above the snow so that

$$\partial\bar{T}_d/\partial z \approx \partial\bar{T}_a/\partial z \quad (18)$$

On the basis of these assumptions, (16) becomes

$$L_v + Q_a = \left(\frac{\eta L_v^2}{pR'T_d^2} + c_p\right)K_{h+1}\bar{p}_{h+1}(\partial\bar{T}_a/\partial z)_{h+1} \quad (19)$$

From (1) and (19), the following solution for K_{h+1} is obtained

$$K_{h+1} = \frac{F_a - I_h{}^{\downarrow}(1-\beta) - R_s - c_w(T_w - T_h)P_w}{\left(\frac{\eta L_v^2}{pR'T_d^2} + c_p\right)\bar{p}_{h+1}(\partial\bar{T}_a/\partial z)_{h+1}} \quad (20)$$

Knowing that significant errors may exist in the radiation and rate of melt terms in the above equation, one of two methods can be used in an attempt to obtain 'correct' values of the exchange coefficient, through solution of this equation:

(a) It may be assumed that errors in radiation and melt terms are randomly distributed. In this case, the proper function for K is approached by averaging all individually computed values; the larger the number of values used in the average, the closer the correct function is approached. This was the method used by Sverdrup and Wallén. Its shortcomings arise primarily from its dependence on the initial assumption of a random error distribution; an assumption that very well may not be valid. A second shortcoming arises from the possibility that when, as Sverdrup and Wallén have done, individually computed coefficients are plotted against windspeed, other parameters upon which K may be dependent and which have not remained constant for all cases used may lead to a scattering of K values which cannot be identified separately from scattering produced by errors in radiation and rate of melt terms.

(b) It may be assumed that the largest errors in radiation and rate of melt terms are not randomly distributed. In this case, the data must be sorted and values of K computed only for selected periods during which the probability of errors in these terms is a minimum. This is the method which has been used in the present study. The danger in this method lies in the possibility that a subjective bias may be introduced in the selection of data. In an attempt to avoid this latter problem, observation periods for which coefficients were computed in the present study were selected before calculations of K were carried out on the basis of the following criteria: (1) skies were completely overcast throughout the periods used; (2) bases of the overcasts were within a few hundred feet of the glacier surface; and (3) no appreciable changes in air temperature and windspeed near the glacier surface occurred during the periods of observation. Under these conditions, maximum possible reliability was obtained in readings of incoming and reflected short-wave radiation with the pyrheliometers, the effective long-wave radiation could be

reasonably estimated on the basis of a black body radiational exchange between the snow and clouds, and finally, monotony of wind and temperature conditions during each period allowed calculation of average windspeeds and temperatures with minimum possible error.

Calculation of the temperature lapse rate at one centimeter—Because the term, $(\partial \overline{T}_a/\partial z)_{h+1}$ cannot be measured directly, it is common to estimate this lapse rate from a curve fitted to values of $\overline{T}_a$ measured at three or more heights above the snow surface.

On Lemon Creek Glacier, copper constantan thermocouples of 30-gage wire were used to measure air temperatures at heights of 8, 27, 64, 125, 216, 336, 512, and 729 cm above the snow surface. (These represent initial heights at which thermocouples were mounted. Due to settling of the thermocouple mast in the snow and lowering of the glacier surface by ablation, thermocouple heights varied throughout the season.) A reference junction was kept in a thermos bottle tightly packed with wet snow. Output differences between thermocouples in the air and the reference junction were recorded on a Speedomax recorder which operated continuously, and recorded a complete set of temperature readings approximately once a minute.

For stable lapse rates, Sverdrup fitted observed values of $(\overline{T}_a)_{h+z}$ by the curves

$$(T_a)_{h+z} = \Delta T_1 + \Delta T_2 z^{1/n_u} \qquad (21)$$

where n_u is calculated from a power curve fitted to observed windspeeds; ΔT_1 an ΔT_2 are constants. The value $(\partial \overline{T}_a/\partial z)_{h+1}$ was then obtained by differentiation of the above equation.

Wallén fitted his observed temperatures by the curve

$$(T_a)_{h+z} = \Delta T_2 z^{1/n_T} \qquad (22)$$

where both ΔT_2 and n_T were calculated from the temperature data.

Comparisons were made in the present study between values for $(\partial \overline{T}_a/\partial z)_{h+1}$ as computed from (21) and (22), as well as values computed from a curve of the form

$$(T_a)_{h+z} = \Delta T_1 + \Delta T_2 z^{1/3} + \Delta T_3 \ln \frac{(z+z_0)}{z_0} \qquad (23)$$

which was found to give a better fit to observed data than the other two curves.

Use of any of these three curves to calculate the lapse rate at one centimeter was found unsatisfactory for the following reasons:

(1) For a particular period, the value of the lapse rate at one centimeter obtained by differentiation of any of the three curves was highly dependent on the heights at which temperature measurements were made, and the type of curve fitted to the observed temperatures. Naturally, values of K computed using these lapse rates were likewise very dependent on heights at which temperature measurements were made, and the type of fitted temperature curve used.

(2) Sets of K values computed for a spectrum of windspeeds were so scattered that a simple expression for the variation of K with windspeed could not be established. This could be a result of a deficiency in the theoretical expression for turbulent transfer of energy, or from errors in radiation or rate of melt terms. In the possibility, on the other hand, that the principal deficiency might lie in values of the lapse rate at one centimeter obtained by differentiation of fitted curves, the investigation was carried one step further by arbitrarily replacing the differential term, $(\partial \overline{T}_a/\partial z)_{h+1}$, in (20) by the finite difference, $(\overline{T}_a)_{h+1} - T_h$. Eq. (20) then becomes

$$K^* = \frac{F_a - I_h{}^{\downarrow}(1-\beta) - R_s - c_w(T_w - T_h)P_w}{\left(\frac{\eta \epsilon L_v^2}{pR'T_d^2} + c_p\right)\bar{\rho}_h[(T_a)_{h+1} - T_h]} \qquad (24)$$

where the notation, K^*, is used to differentiate exchange coefficients computed using finite temperature differences from coefficients using differential temperature lapse rates.

A hypothetical temperature for a height of one centimeter as computed from fitted curves was found to be much less dependent on heights at which temperatures to which curves were fitted were measured and choice of curve used to fit the observed temperatures than was the computed differential lapse rate at one centimeter. Table 7 shows values of mean temperatures computed from thermocouple data for an observation period selected at random. A comparison of the variations in computed temperature and lapse rate at one cm

TABLE 7 – *Observed mean temperatures at various heights over the snow surface, July 11, 1954*

z	$(\overline{T}_a)_{h+z}$	z	$(\overline{T}_a)_{h+z}$
0	0°C	166	4.5
8	3.5	293	4.6
27	3.9	462	4.6
64	4.2	679	4.4
75	4.2		

TABLE 8 – *Comparison of variability in computed temperatures and temperature lapse rates at a height of one cm*

Item	$(\overline{T}_a)_{h+1}$	Deviation from mean	$\left(\frac{\partial \overline{T}_a}{\partial z}\right)_{h+1}$	Deviation from mean
		pct		pct
Curve fitted to data in Table 7 at all levels $T = 2.731 - 0.247 s^{\frac{1}{2}} + 0.600 \ln s$	2.7	−4	0.52	+41
Curve fitted to data in Table 7 from 8, 27, and 64 cm only $T = 2.846 - 0.001 s^{\frac{1}{2}} + 0.330 \ln s$	2.8	0	0.33	−11
Curve fitted to data in Table 7 from 8, 27, and 64 cm only $T = 2.9 s^{0.088}$	2.9	4	0.25	−33

resulting from use of different curves and observation heights in the computations is shown in Table 8.

In Table 8 are shown values of $(\overline{T}_a)_{h+1}$ and $(\partial \overline{T}_a/\partial z)_{h+1}$ computed from curve for (23) fitted first to all data in Table 7, and then to temperatures from the lowest three observation levels only. In the third row are values computed from curve for (22) fitted to data from the lowest three levels.

Computed exchange coefficients—As stated earlier, air temperatures remain above freezing with very few exceptions throughout the ablation season on Lemon Creek Glacier. As a result, observations used in this paper were all taken with stable lapse rates near the snow surface. Conclusions from the present study cannot therefore be extended to adiabatic, or unstable lapse rate conditions.

Quantities used to calculate K^* and values of K^* obtained are shown in Table 9. Figure 3 demonstrates these values plotted against $\bar{u}_{25}$, the average windspeed measured during each period with a standard three-cup anemometer at a height of 25 cm above the snow surface. The straight line shown was fitted by least square methods, and is given by

$$K^* = 0.0075\ (\bar{u}_{25} - 100)\ \text{cm}^3\text{sec}^{-1} \qquad (25)$$

where $\bar{u}_{25}$ is always greater than 100 cm sec^{-1}.

For comparison, similar values of K^* were computed using Wallén's observations under stable conditions on the Kårsa Glacier. In place of the temperature lapse rate at one centimeter, Wallén's values of θ (temperature at one cm in °C) were used. Windspeeds at 25 cm were computed from the equation: $\bar{u}_{25} = \bar{u}_1 25^{1/n_\theta}$. Data used were those appearing in Table X of Wallén's paper, for Periods IV through XIX. Values of K^* obtained are shown in Figure 4. In Figure 5, a straight line fitted by least-square methods to these values is shown in comparison to that obtained from the present studies.

The two linear functions for K^* shown in Figure 5 are in reasonably good agreement. The large scatter of coefficients computed from Wallén's data therefore may be a result of randomly distributed observation errors. That for any given windspeed Wallén's data leads to higher values of K^* is to be expected, for, if the present analysis of effective long-wave radiation under cloudy skies is correct, Wallén has underestimated his long-wave radiation terms, and thereby gotten values for $Q_a + L_a f$ which are somewhat too large.

At least in the presence of a stable lapse rate over the snow surface, the use of an expression for energy transfer by turbulence at the surface based on the finite temperature difference in the first centimeter of air above the snow and a coefficient

TABLE 9 – *Quantities used to calculate K^*, and values of K^* obtained*

Date (1)	Duration (2)	F_a (3)	R_s (4)	$I_h(1-\beta)$ (5)	$c_w(T_w - T_h)P_w$ (6)	$Q_a + L_a f$ (7)	$\bar{u}_m$ (8)	$\overline{T}_{h+1}$ (9)	K^* (10)
	hr.						cm/sec	°C	cm³/sec
June 15, 1954	6	0.091	0.028	0.064	0.000	...	80	...	...
July 11, 1954	4	0.156	0.028	0.046	0.000	0.082	250	3.0	1.04
July 11, 1954	4	0.132	0.027	0.014	0.007	0.084	250	3.0	1.09
July 21, 1953	3½	0.154	0.020	0.064	0.000+	0.070	280	2.1	1.25
July 21, 1953	5	0.186	0.020	0.094	0.000+	0.072	280	2.1	1.29
July 21, 1953	4	0.121	0.019	0.020	0.010	0.072	280	2.0	1.40
July 8, 1953	4	0.356	0.042	0.062	0.017	0.235	310	6.0	1.63
July 19, 1954	4	0.050	−0.005	0.000	0.000	0.055	360	1.1	1.87
July 12, 1954	5½	0.179	0.020	0.042	0.003	0.114	375	2.1	2.08
July 8, 1953	4	0.414	0.041	0.032	0.010	0.331	380	5.5	2.29
June 20, 1953	4	0.171	0.018	0.032	0.003	0.118	450	1.8	2.47

Values in columns 3 to 7 are in cal cm^{-2} min^{-1}.

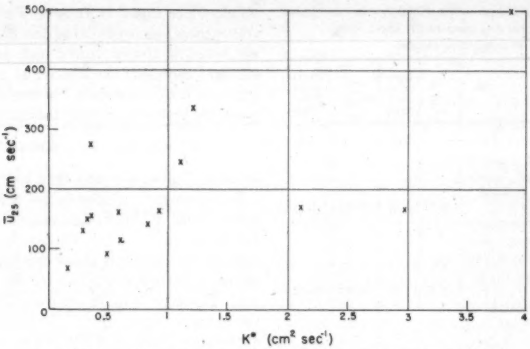

FIG. 4 – Values of the exchange coefficient K* computed from Wallén's data

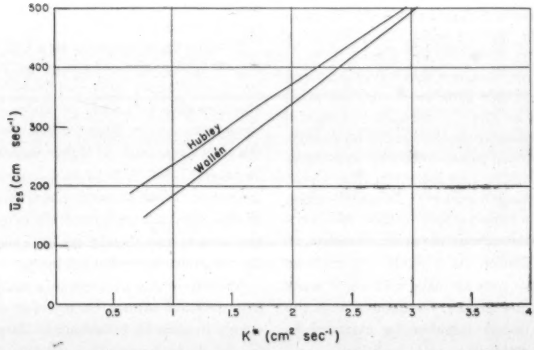

FIG. 5 – Comparison of linear curves fitted to values of K* as computed from Wallén's data and from the author's data

which is a linear function of windspeed appears to have a definite, practical value.

That the linear functions for K^* shown in Figure 5 approach the magnitude of the molecular coefficients more rapidly than does the wind speed approach zero, is possibly related to the existence of a pseudo-laminar boundary layer adjacent to the snow surface during periods of very light winds, within which the exchange coefficient follows a different function. On a few occasions, the existence of this pseudo-laminar layer became visible on the glacier. These periods were characterized by an extremely stable atmosphere and low windspeeds. A very fine thermocouple moved up and down vertically from the relatively cool surface layer of air into the much warmer air layer some distance above the surface, revealed a very sharp intervening boundary. Temperature observations taken during one of these periods are shown in Figure 6. When distant objects were viewed from a height above the surface such that this boundary intersected their images, it was observed that the images were split and discontinuous along this boundary. Further, the portions of the images viewed above this boundary showed a pattern of rapid and irregular shimmering. Those parts of the images viewed below the boundary showed no shimmering, but rather a slow, gently rising and falling as in a stable wave motion. Clearly, this boundary was one along which there was very strong wind shear,

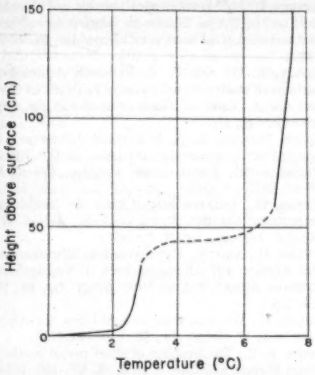

FIG. 6 – Vertical temperature distribution through the pseudo-laminar boundary layer. Dashed line represents lapse rate estimated from thermocouple moved up and down between fixed thermocouple levels

and across which very little turbulent transfer of momentum or heat took place. Further, the lack of shimmering within the lower layer indicated that vertical transfer of heat and momentum by turbulence was nearly absent in this layer. The transfer of heat through the layer must therefore be predominantly by radiation, while the temperature lapse rate within the layer is then primarily determined by divergence of the radiative flux passing through the layer. Conceivably, a plot of the exchange coefficient with height under these conditions would have shown a first order discontinuity at the upper boundary of this layer.

It is felt that the present study has thrown further light on the use of an exchange coefficient in the practical analysis of turbulent heat transfer at a snow surface. More extensive and rigorous treatment of turbulence is definitely required, but must await the development of more reliable and accurate means for measuring the surface net energy exchange and radiation terms.

Role of atmospheric turbulence in energy exchange on the glacier during the ablation season—The role of heat exchange by turbulence in producing melt is a most important one on the Lemon Creek Glacier where air temperatures are above freezing and high winds may occur frequently during the ablation season.

During the passage of one storm in 1953, 30 cm of snow with a water equivalent of 15 cm were melted in a single day at the micrometeorological station on the glacier. The number of warm storms passing over the glacier in a single ablation season can largely determine whether the glacier will end the season with a positive or negative mass budget. The conclusion is reached, therefore, that the number and intensity of summer storms are the crucial factors in determining the magnitude of glacier ablation in the Juneau Ice Field. On the other hand, storms are also the primary factors in accumulation in the ice field; the location of the atmospheric freezing level relative to the glaciers determines whether a given storm will lead to accumulation or ablation. Of considerable interest is the fact that freezing levels during summer storms on the ice field frequently intersect higher parts of the ice field. A good example is the 1953 storm mentioned earlier in which 30 cm of snow on the upper Lemon Creek Glacier was melted in one day. This same storm brought heavy accumulation to the elevated parts of the Juneau Ice Field.

CONCLUSIONS

The following conclusions concerning the energy exchange at an isothermal, melting snow surface can be drawn from the present analysis.

Over large grained 'snow' such as is found in summer on temperate glaciers, the albedo must be expected to vary not only with the physical state of the snow surface, but also with angle of incidence of insolation and with cloudiness. In the present study, the diurnal average albedo of snow on Lemon Creek Glacier on overcast days was found to be 1.07 times the diurnal average on cloudless days during the summer months. As a result, although diurnal insolation received at the snow surface on an overcast day averaged 60 pct of that received on a clear day, the amount absorbed by the snow on an overcast day averaged only 50 pct of that absorbed on a clear day.

With a frequent occurrence of overcasts over the glacier in which cloud temperatures were higher than the temperature of the snow surface, that is, above 0°C, the net long-wave radiation exchange at the snow surface was often positive. The effect of these warm temperature overcasts was found to be such that in general the net total radiation transfer to a level snow surface on the Juneau Ice Field is greater during an overcast 24-hour period than during a clear 24-hour period.

Particularly with the presence of low clouds, the cloud temperature has such a strong influence on long-wave radiation exchange at the glacier surface, that it is not feasible to estimate the net long-wave radiative transfer through use of empirical

equations which do not take the cloud temperatures into account.

Rates of rainfall necessary for rate of heat transfer to the melting snow by rain to become significant compared to other heat transfer processes were found to be considerably more than rainfall rates measured on the Lemon Creek Glacier even during passage of the wettest storms. It is concluded that heat transfer to snow by rainfall in general will not be significant unless the snow temperature is below freezing so that the rainwater freezes as it percolates through the snow, thereby giving up the heat of fusion.

It was found that the rate of heat transfer to the snow by turbulence could be related to wind and temperature distribution over the snow by use of a transfer coefficient K^* which is a linear function of windspeed, times a temperature function calculated from a power curve fitted to mean air temperatures measured at three or more heights above the snow surface.

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Accuracy of Determination of Stream Lengths from Topographic Maps

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Abstract—Two methods are used to measure stream lengths from topographic maps: (1) using streams printed in blue, or (2) inserting streams into the drainage net wherever there are V-shaped contours. The accuracy of these two methods was tested by comparing measurements taken from maps with the streams as measured in the field.

In basins with area less than one half square mile, a paired *t*-test between field measurements and the contour method showed no significant difference while a paired *t*-test between field measurements and streams marked in blue did show a significant difference. In basins with area varying from 0.5 to 2.68 sq mi, total stream lengths and drainage densities obtained using streams in blue are always smaller than those obtained by field measurement. This indicates that a significant difference exists. A paired *t*-test showed no significant difference between values of field measurement and the contour method.

This statistical study indicates that, at least in very small watersheds, streams should not be measured from topographic maps using the streams printed in blue. The contour method may be used.

The determination of stream lengths and drainage density is of great importance in the quantitative geomorphology of drainage basins. At least two methods are in present use when data are obtained from topographic maps. The Corps of Engineers, Hydrographic Office, and other government agencies, following the example of *Horton* [1932, 1945] and *Langbein* and others [1947], measure lengths of streams which are actually inserted in blue on the map. This method seems inaccurate as the blue is inserted only where water is present when the map is drawn, and the presence or absence of water in the channel is often a seasonal occurrence.

The adaptation put into use by Strahler is to insert a stream into the drainage net wherever the V-shaped contours indicate a channel might be present [*Miller*, 1953]. Although some subjectivity may enter here, it is the practice to insert a stream only where there is a definite notch in the contours (see Fig. 1b). The purpose of the present paper is to investigate the validity of these two methods.

Case 1 includes basins smaller than 0.5 sq mi. All map measurements were taken from quadrangles whose topography was done from aerial photographs by multiplex methods. The maps were of 1950 edition with a scale of 1:24000 and a contour interval of 20 ft. The area from which the basins were chosen lies in the Allegheny section of the Appalachian Plateau in northern Pennsylvania. All are part of the larger drainage system of the Allegheny River.

To establish a standard to which the two methods could be compared a number of streams were measured in the field; 61 first-order streams, 12 second-order, and 2 third-order. Together these totalled 11 separate and complete basins. These were the standards used for comparison.

In doing the field work it was noticed that there were a number of streams carrying water at the time of measurement (spring) which were not marked in blue on the maps. In general, these were narrow first-order streams not more than one or two feet wide. Some were on wooded slopes. Thus they may not have been visible on aerial photographs. There were several cases where the blue of streams was carried beyond the point considered the head by field inspection.

A number of first- and even second-order streams were not shown on the maps, even by V-shaped contours. In most cases these were fairly short streams (100 ft more or less) which were tributary to larger valleys. Figure 1a is a contour map showing the stream length. Figure 1b shows the drainage net using the contour method, and Figure 1c shows the basin as measured in the field.

In the field streams were measured with a tape and stream gradients were measured with Brunton compass or Abney level. For use in comparison with measurements taken from a map the lengths were corrected to horizontal distances. Areas were taken by planimeter from the topographic sheets. These varied in size from 0.097–2.68 sq mi. Changes in stream net did not change the overall basin area.

Table 1 shows the total stream lengths and drainage densities for the first case as determined by field measurement, the method of V-shaped contours and the method of using blue streams.

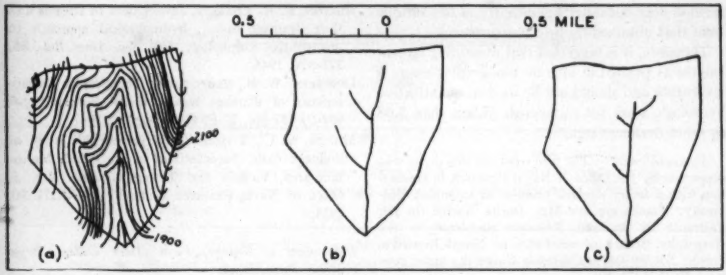

FIG. 1 – Contour and drainage maps of Heth Run; (a) contour map with stream traced from topographic sheet; (b) drainage net using V-shaped contours; (c) drainage net as measured in the field

TABLE 1 – *Stream lengths and drainage densities, watershed area less than 0.5 sq mi*

Area	Field measurement		Contour method		Blue method	
	ΣL	D_d	ΣL	D_d	ΣL	D_d
sq mi	mi		mi		mi	
0.097	0.464	4.78	0.303	3.12	0	0
0.169	0.671	3.97	0.948	5.61	0	0
0.197	0.707	3.59	0.682	3.46	.568	2.88
0.237	0.435	1.84	0.834	3.52	.455	1.92
0.242	0.760	3.14	0.757	3.13	.682	2.82
0.252	1.196	4.75	0.985	3.91	.530	2.10
0.254	0.957	3.77	1.060	4.17	.493	1.94
0.286	0.890	3.11	0.758	2.65	.568	1.99
0.410	1.399	3.41	1.274	3.11	1.060	2.59
0.416	0.699	1.68	1.440	3.46	.758	1.82
0.459	1.366	2.98	1.550	3.38	1.440	3.14

ΣL = total stream length.
D_d = drainage density.

TABLE 2 – *Stream lengths and drainage densities, watershed area 0.5–2.68 sq mi*

Area	Field measurement		Contour method		Blue method	
	ΣL	D_d	ΣL	D_d	ΣL	D_d
sq mi	mi		mi		mi	
0.545	2.865	5.26	2.46	4.51	1.38	2.53
0.764	2.247	2.94	2.311	3.02	2.01	2.63
1.50	4.203	2.80	7.099	4.73	2.56	1.71
1.64	8.796	5.36	7.691	4.69	8.38	5.11
1.64	3.610	2.20	4.850	2.96	3.26	1.99
1.652	9.727	5.89	6.210	3.76	3.65	2.21
2.680	15.767	5.88	8.38	3.13	6.41	2.39

ΣL = total stream length.
D_d = drainage density.

A paired *t*-test for the field measurements and contour method shows a mean difference of 0.226 which can be expected to occur 50 – 60 pct of the time due to chance alone. Hence this difference is not significant. A paired *t*-test between the field measurements and the measurements using the streams in blue shows a mean difference of 1.435 which gives a probability of two per cent. This difference is significant.

Case 2 is concerned with watersheds varying in area from 0.5–2.68 sq mi. Again streams measured in the field were compared with measurements taken from maps. In this case the maps used were on a scale of 1:62500, with a contour interval of 20 ft. These streams include 267 of first order, 62 of second order, 18 of third order, 4 of fourth order, and one of fifth order. Together they comprise seven complete basins. All are in the Appalachian Plateau, five in Ohio and two in Pennsylvania.

Table 2 shows the total stream lengths and drainage densities as determined by field measurement, contour method and method of using streams in blue. From the table it is evident that since the drainage densities obtained by the blue line method are always smaller than those obtained by field measurement, a paired *t*-test would show a significant difference between the two values. A paired *t*-test carried out for the field measurement and contour method shows a mean difference of 0.50. This difference can be expected to occur 40–50 pct of the time due to chance alone, therefore, the difference is not significant.

From the statistical evidence taken from these two samples, then, we can conclude that stream lengths and drainage densities vary significantly from the actual field data when obtained by measuring the streams as marked in blue on the topographic sheets. However, drainage density and stream lengths obtained by using the contour

method does not differ significantly in this sample from that obtained by field measurement.

Therefore, it is suggested that measuring stream lengths as printed in blue on topographic maps is inaccurate and should not be used in quantitative hydrologic work for watersheds of less than 2.68 sq mi of drainage area.

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Anisotropy in Rocks under Simple Compression*

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Abstract—Compressional velocities through samples of several types of rocks have been measured while the samples were subjected to simple compression in a hydraulic press. Velocity measurements were made in directions parallel to and perpendicular to the direction of the compression, with the amount of compression varying from zero up to the rupture point. All measurements were made at room temperature and with no confining pressure other than that of the atmosphere.

Velocities in a direction parallel to the compression increased with compression in a manner somewhat similar to the increase found by other workers in samples subjected to hydrostatic pressures. Velocities in a direction perpendicular to the compression also increased, but at a much lower rate. The differences in the two velocities amounted to over ten per cent in some cases.

The differences in velocities are large enough to suggest the possibility of making a rough determination of the state of strain in the neighborhood of a recognized active fault which is known or suspected to be near vertical. Possible applications toward the prediction of rock-bursts are also suggested.

Introduction—Two important developments in recent years have combined to facilitate the direct measurement of seismic velocities in small laboratory samples of elastic solids. The wartime-inspired electronic techniques of high frequency pulses have made possible the accurate measurement of the minute time interval required for an elastic pulse to traverse a sample whose major dimension is of the order of a few centimeters. Investigations at the Bell Telephone Laboratories and by others on the piezo-electric and electrostrictive effects of certain crystals have provided the experimental seismologist with an effective means of converting an electromagnetic pulse into an elastic pulse, and vice versa.

It is thus now possible to control accurately certain important conditions of a velocity determination such as temperature, pressure, and homogeneity of sample, which are necessarily uncontrollable or even unknown in the field. The result is that a much clearer picture is beginning to emerge of the effects on seismic velocities and related elastic parameters of pressures and temperatures corresponding to depths as great as or greater than that of the Mohorovicic discontinuity.

Most of the recent investigations have been concerned with the effects on seismic velocities of hydrostatic pressure or temperature or both. *Hughes* and *Kelly* [1953] combined hydrostatic pressure results with velocity measurements made under simple axial compression to derive both Lamé's and Murnaghan's elastic constants for polystyrene, iron, and pyrex. The present work was undertaken to determine the effect of simple axial compression on the longitudinal velocities in several rocks which occur commonly in the Earth's crust.

Experimental procedure—Figure 1 is a block diagram of the electronic components of the experimental apparatus. The output of the trigger generator has a square waveform which is adjustable in amplitude and duration. This square-wave output of the pulse generator, of duration about one microsecond, and of adjustable amplitude, is impressed across a barium titanate crystal which makes mechanical contact with the rock sample. An identical barium titanate crystal converts the transmitted elastic energy back into electrical impulses, which are fed into the y-amplifier of the cathode-ray oscilloscope. Meanwhile, the trigger-generator output has also been passed through an R-C differentiator, which produces a positive spike from the leading edge of the square wave, and a negative spike from the trailing edge. The negative spike triggers the oscilloscope sweep, so that the start of the sweep is delayed by an adjustable amount of time equal to the duration of the trigger pulse.

The purpose of delaying the start of the sweep is to permit use of an expanded time scale for displaying the beginning of the transmitted pulse. The particular equipment used in these experiments did not permit a very accurate measurement of the amount of this delay, so that relative times were

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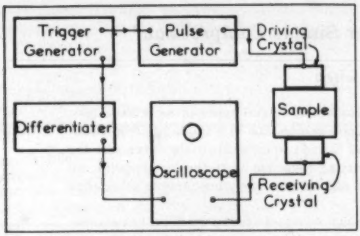

FIG. 1 – Block diagram of the electronic components

measurable with accuracy about an order of magnitude higher than absolute times. The accuracy of relative times was limited mainly by the gradual character of the beginning of the transmitted pulse after its passage through the rock. Calibration of the oscilloscope time scale was accomplished prior to each set of measurements by impressing the output of a crystal oscillator on the Y-input terminals of the oscilloscope.

Figure 2 is a schematic diagram of the mechanical components of the experimental apparatus, when set up to measure velocity parallel to the direction of compression. Force from each opposing jaw of the hydraulic press is transmitted to the rock sample through a steel thrust ring and a cylindrical steel thrust block. The core of the thrust ring contains a barium titanate crystal against the thrust block. This crystal is backed up by a steel electrode and a backing disk of bakelite and hard rubber.

The pulse-generator output is impressed across the crystal between the thrust block and the steel electrode. Because of the strong electrostrictive effect in pure barium titanate, a compressional pulse is generated by the crystal. This elastic pulse travels through one thrust block, then through the rock sample, and then through the other thrust block, where the inverse electrostrictive effect produces an electric field across the receiving crystal. It is the voltage difference between thrust block and electrode across the receiving crystal which is displayed, after suitable amplification, on the oscilloscope.

To measure pulse travel times in a direction perpendicular to the axis of simple compression, the two crystals and steel electrodes are clamped against opposing faces of a cubic specimen which are normal to the faces against the thrust blocks. Sheets of aluminum foil about 0.001-inch thick between crystal and sample serve as the other electrodes in place of the thrust blocks.

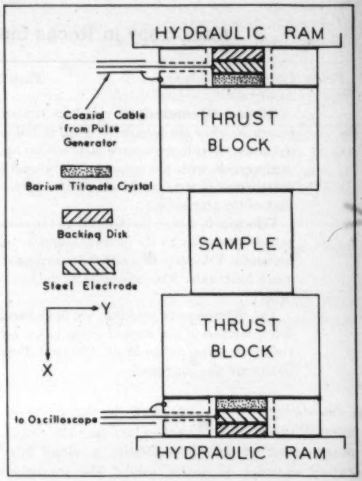

FIG. 2 – Schematic diagram of the mechanical components

Figure 3 is a view of the jaws of the hydraulic press with a ruptured sample of Barre granite between the thrust blocks. The principal plane of failure of this sample makes an angle of about 30° with the axis of compression.

Materials studied—Seven different types of rock were studied, including igneous, metamorphic, and sedimentary samples. These samples were all taken from the collection of the Dunbar Laboratory of Harvard University, and were selected to include a number of representative rock types which occur commonly in the Earth's upper layers. Some of these same rock types have been studied more or less extensively by other investigators, and many of their characteristics are listed in the Handbook of Physical Constants [*Birch* and others, 1942].

The following is a list of the samples investigated, and the locations from which they were originally obtained:

Barre granite from the commercial quarries at Barre, Vermont.

Vinalhaven diabase, Vinalhaven, Maine.

Cambridge slate from a water tunnel about 360 ft below the surface in Medford, Mass.

Soapstone, a commercial variety from Aberene, Virginia.

Serpentine from the Vermont Talc Company Quarry near Chester, Vermont.

FIG. 3 – Ruptured sample of Barre granite in hydraulic press

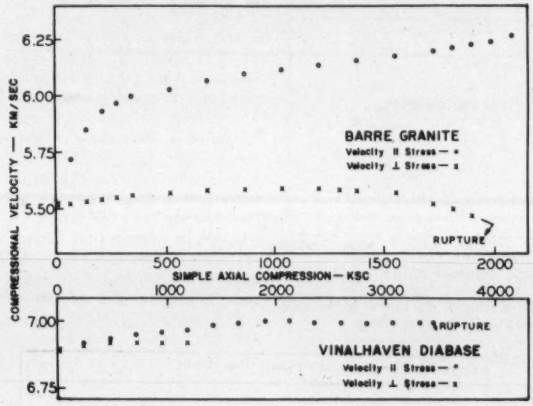

FIG. 4 – Variation of observed velocities with axial compression for Barre granite and Vinalhaven diabase

Catskill sandstone, Devonian age from 660 ft below the surface in a test boring for the East Delaware Tunnel near Pepacton, N. Y.

Pittsford marble from Pittsford, Vermont.

Results—Figure 4 shows for Barre granite and Vinalhaven diabase the observed variations of longitudinal velocities parallel to and perpendicular to the axis of compression. The velocity in granite parallel to the direction of stress increases very rapidly with stress at the lower end of the curve, then more slowly up to a stress just below the rupture point. Perpendicular to the stress, the velocity in granite increases very slightly up to about half the stress ultimately required to rupture the sample. From that point up to the rupture point, the velocity actually decreases slightly with increasing stress. With an axial compression on Barre granite of 1900 kg/cm², or slightly less than enough to rupture the specimen, the longitudinal velocity in the direction of the compression

is nearly 14 pct higher than the velocity measured perpendicular to the compression. The corresponding effect in Vinalhaven diabase is much less, amounting to a difference of about one per cent at an axial compression of 1180 kg/cm².

The work of other experimenters has shown that a plot of longitudinal velocity in granite versus hydrostatic pressure on the sample also has the characteristic that the velocity increases rapidly with low pressures, then more slowly with higher pressures. Figure 5 shows unpublished results of some measurements made by Birch on Barre granite. These were made at room temperature, and at pressures from atmospheric up to those corresponding to depths greater than the Mohorovicic discontinuity. Again the curve is quite steep at the low pressure end, and becomes less steep at higher pressures. However, the entire stress range in Figure 4 corresponds to only the very steep portion of Figure 5. The two types of experimental results, for hydrostatic and for axial compression, are plotted in Figure 6 on the same scale for stress.

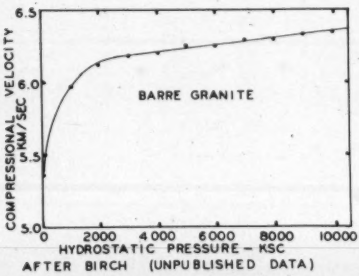

FIG. 5 – Variation of velocity with hydrostatic pressure for Barre granite (after Birch)

The zero-stress velocity of Barre granite was found to vary from 5.29 km/sec to 5.52 km/sec in different samples from the same region of the same quarry. While all three curves in Figure 6 start at approximately the same point, the sample used for the axial compression measurements was not the same sample as that used for the hydrostatic pressure measurements of Birch, and the agreement at zero stress is merely fortuitous.

Figure 7 shows the variation of compressional velocity with axial compression in four metamorphic and sedimentary rocks: slate, soapstone, serpentine, and sandstone. For these, measurements of velocity were made only parallel to the axis of compression. Of the seven types studied in this investigation, Cambridge slate was the only one possessing a significant degree of anisotropy in the unstressed state. For this reason, velocity measurements were made on the slate when compressed parallel to and perpendicular to its cleavage direction.

The degree of elastic anisotropy induced in Pittsford marble by simple axial compression is shown in Figure 8. This marble exhibited an additional effect not found in connection with any of the other six rock types considered. When measurements were made parallel to the axis of compression, a fast arrival could barely be detected. It had a very gradual beginning, and was followed by a much sharper arrival carrying much more energy. The early arrival could not be detected in measurements of velocity perpendicular to the axis of compression in which the steel thrust blocks did not constitute a portion of the wave path. It may be that the fast arrival is transmitted via a gross elastic structure remaining from

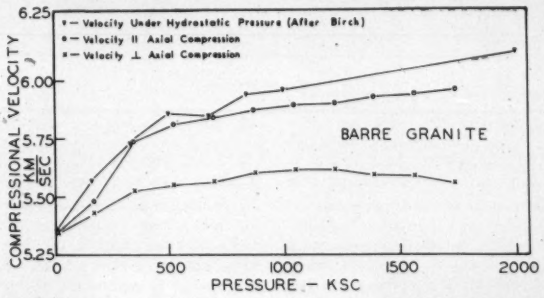

FIG. 6 – Variation of velocities with axial compression and hydrostatic pressure for Barre granite

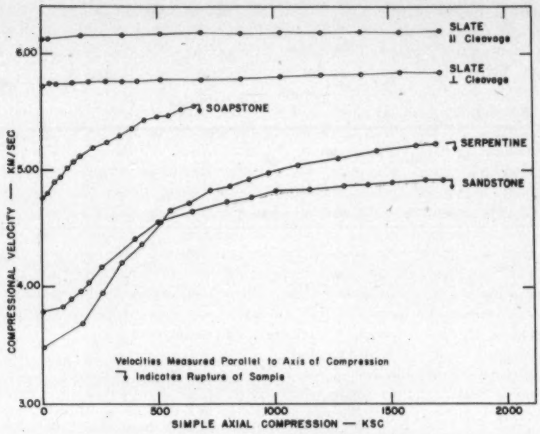

FIG. 7 – Variation of velocity with axial compression for slate, serpentine, soapstone, and sandstone

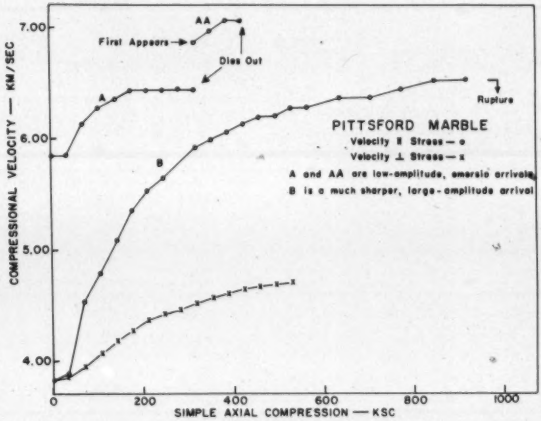

FIG. 8 – Variation of velocities with axial compression for Pittsford marble

the parent limestone, while the much slower, large energy wave is characteristic of the fine grains of the marble.

Of the seven rock types considered, the Vinalhaven diabase and the Cambridge slate were the only ones which failed to show an increase of at least ten per cent in the velocity parallel to axial compression when the compression was carried to or near to the rupture point of the specimen.

Discussion—The degree of anisotropy which can be induced in a laboratory specimen of granite by simple axial compression readily suggests a possible method for determining the state of stress in rocks *in situ* in cases where stress is known or suspected

to be accumulating. In the vicinity of San Francisco Bay, geodetic measurements have indicated a slow drift of triangulation points on the seaward side of the San Andreas Fault to the northwest relative to points on the landward side [*Hayford* and *Baldwin*, 1908; *Whitten*, 1948]. This fault broke at the surface in 1906 in a sense which agrees with the geodetic measurements. It is a nearly vertical fault, and the 1906 movements were nearly pure strike slip. While the underlying cause for the secular accumulation of strain energy in the rock adjacent to the San Andreas Fault and its periodic release in the form of rupture along the fault are unknown, both of these effects are consistent with a regional axial compression of the Earth's crust in a direction not far from north-south.

If such a regional compression does exist, careful field measurements of seismic velocities in both north-south and east-west directions might reveal elastic anisotropy indicative of that compression. Such measurements would necessarily have to be along rather short profiles to insure reasonable homogeneity of the rocks along the two profiles, and also to insure that the wave paths did not penetrate so deeply into the crust that other unknown factors such as dipping interfaces and lateral variations in temperature distribution might mask the compressional anisotropy. The limitation of shallow penetration is not otherwise restrictive, inasmuch as the movement of geodetic triangulation points indicates that the surface rocks are probably partaking of any possible compression as much as the deeper rocks.

Measurements of the nature suggested could be made at any time to reveal the possible existence of anisotropy. To pin the cause of the anisotropy definitely on regional compression, it would be necessary to repeat the measurements on exactly the same profiles after an interval of some years, and to show that the degree of anisotropy had increased in the intervening years if no major earthquake had occurred, or had decreased due to release of strain if a major shock had occurred in the interval.

Another situation in which stress is known to have accumulated is in the walls of mines which are subject to rockbursts. *Obert* [1939] noted that the compression of a supporting pillar in a mine should cause the velocity to increase along the axis of the column. His methods of velocity determination predated the modern pulse techniques, so that he failed to find that the velocity perpendicular to the pillar would not increase nearly as much as the velocity along the axis. To measure anisotropy in the walls of mines as a possible means of predicting rockbursts, it would be necessary to make one of the velocity determinations normal to the wall and with the rock *in situ*. If such a process should prove to be economically feasible, the degree of anisotropy found should provide a means of rockburst prediction.

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A Treatment of Self-Gravitational Strains in the Earth

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Abstract—Self-gravitational forces acting alone on a spherical body produce non-hydrostatic strain states. An analysis of these strains and attendant deformations, as applied to the Earth, shows that an extension type of strain, characterized by radial extrusion of material, exists in the upper mantle. Also, a radial displacement at the Earth's surface of about 188 km can be attributed to this self-gravitational attraction.

The gravitation of a body toward its center of mass causes some overall contraction of the body. The amount of contraction produced is that required to bring about a static strain state sufficient to hold the body in equilibrium with the gravity forces. If the body is uniform in density and physical properties relating stress to strain, the problem of deriving an analytical expression for these self-gravitational strains is a relatively simple one. The problem is more complex when applied to the variable structure of the Earth's interior. Nevertheless, it is still possible, in the light of present knowledge, to examine some aspects of the distribution of these strains within the Earth and to obtain a measure of the related deformations.

If the Earth is treated as a sphere, these self-gravitational strains may be defined as shown in Figure 1a. Suppose a point P, at an elemental volume of the sphere, is displaced in a radial direction by an amount u to P'. Movement is considered slow enough to permit neglect of inertia. Also, gravity forces are assumed to be acting alone and the strain states produced are taken to be adiabatic. If the spherical shape is kept after deformation, the strains on the dimensions of the element (density ρ) may be expressed as: radial strain $= du/dr = u'$ and tangential strain $= u/r$.

The associated stresses on the elemental volume depend on the nature of the material. For a material essentially elastic in behavior, we have for the radial strain in terms of stresses and elastic constants

$$u' = \frac{\phi - 2\sigma\psi}{E}$$

where ϕ is the radial stress, ψ the tangential stress, E is Young's Modulus, and σ is Poisson's ratio. The tangential strain is

$$u/r = \frac{\psi - \sigma(\phi + \psi)}{E}$$

The foregoing relations may be solved for ϕ and ψ to yield

$$\phi = \frac{E(1-\sigma)}{(1-2\sigma)(1+\sigma)}\left[u' + \frac{2\sigma}{(1-\sigma)}\frac{u}{r}\right]$$

and

$$\psi = \frac{E}{(1-2\sigma)(1+\sigma)}\left[\sigma u' + u/r\right]$$

Since the primary seismic wave velocity P and the secondary seismic wave velocity S in an elastic medium are determined by the elastic constants and the density as

$$P^2 = \frac{E(1-\sigma)}{\rho(1-2\sigma)(1+\sigma)}$$

and

$$S^2 = \frac{E}{2\rho(1+\sigma)}$$

we may express the stress equations in terms of the wave velocities. By making the appropriate substitutions we obtain, after rearrangement and simplification

$$\phi = \rho P^2(u' + 2\,u/r) - 4\rho S^2 u/r \qquad (1)$$

and

$$\psi = \rho P^2(u' + 2\,u/r) - 2\rho S^2(u' + u/r) \qquad (2)$$

On the other hand, if the material behaves as a liquid, the static radial and tangential pressures are equal. We consider that the volumetric strain is

$$u' + 2\,u/r$$

hence the primary wave velocity is

$$P^2 = \frac{\phi}{\rho(u' + 2u/r)}$$

or

$$\phi = \rho P^2\,(u' + 2\,u/r) \qquad (3)$$

The seismic wave velocities are assumed to represent the measure of the modulus of stress to strain for the magnitudes of strain considered. Also, in relations (1) to (3), the strains are treated as differential quantities.

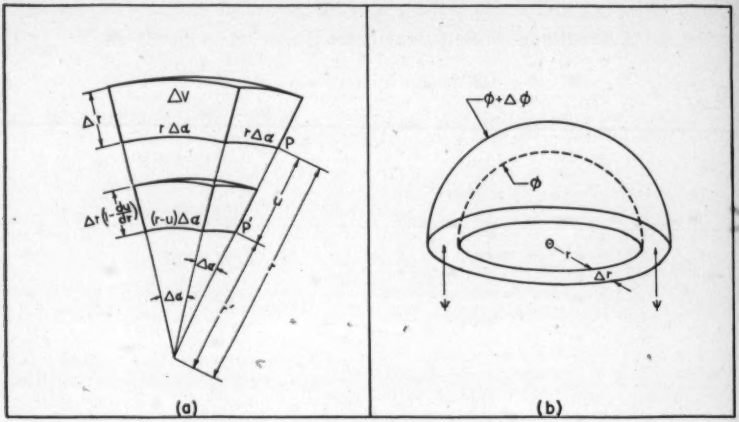

FIG. 1 – Diagrams showing (a) the strains produced in a spherical element by a radial displacement u, and (b) the stresses in a hemispherical shell of radius r

Equilibrium equation—The general form of the static equilibrium equation, in terms of stresses and the body forces, may be derived from Figure 1b. We find it to be

$$\phi' = -\rho g + \frac{2(\psi - \phi)}{r} \qquad (4)$$

In terms of strain in a liquid material, this equation may be written

$$d(\rho P^2 (u' + 2u/r)) = -\rho g\, dr \qquad (5)$$

For an elastic medium, the equation becomes

$$d[\rho P^2 (u' + 2u/r) - 4\rho S^2 u/r] = (-\rho g - 4\rho S^2 (u/r)')\, dr$$

which reduces to

$$d[\rho P^2 (u' + 2u/r)] - 4(u/r)d(\rho S^2) = -\rho g\, dr \qquad (6)$$

The second term in (6) involves a product of differentials and may be neglected without serious error. Eq. (6) then becomes identical in form with (5). From this we may draw a reasonable inference that the equation of form (5) is applicable to static equilibrium in a material having both elastic and liquid properties. The only requirement is that the proper stress-to-strain modulus, as evidenced by the velocity of the primary seismic wave, be used.

In order to solve the differential equation (5) or (6) for the deformation u, we must substitute appropriate functions of the radius representing seismic velocities, densities, and gravity in the Earth, and evaluate constants of integration from stated boundary conditions. Some simplifications are made in this study to permit formal integration, but the fundamental nature of the solution is not altered by doing so. The seismic velocity distribution, as given by *Jeffreys* [1952], can be stated in the form of simple functions which approximate the velocity curve in any one zone of the Earth. The density distribution, as discussed in the following section, must be largely inferred from more meager evidence. However, any reasonable density distribution should serve the purpose of deriving a suitable strain and displacement relation. The gravity function, of course, is derived from the assumed density function.

Density function—Aside from earlier studies of Roche, Wiechert, and others, the most informative investigations of densities in the Earth have been those of *Bullen* [1940, 1954]. By use of the Adams-Williamson relation of seismic velocities to compressibility in the equilibrium equation, he was able to project known density quantities at the surface into the interior by numerical integration. These studies rested on the basic assumption that hydrostatic conditions of strain and stress exist. A significant conclusion from Bullen's work, as dis-

cussed by *Birch* [1954], was that compression alone cannot produce the required density compatible with the Earth's moment of inertia. That is, some intrinsic density increase must be entertained in the upper part of the mantle.

With unlike tangential and radial strains, such as u/r and u' in (5), even less compression is available, at least in the upper mantle, for increasing density with depth. For example, it may be readily seen, with $\phi = 0$ at the surface, that (1) for an elastic material reduces to

$$u' = \left(4\frac{S^2}{P^2} - 2\right)\frac{u}{r}$$

and (3) becomes

$$u' = -2\frac{u}{r}$$

Since u/r is obviously compressive, u' must in both cases be tensile in character. We have then, at the surface, an extension type of strain. This strain state has been described by *Griggs* [1940] as a tensile strain in one principal direction and equal compressive strains along the other two principal axes. All the stresses associated with this strain state are compressive, but the stress along the axis of tensile strain is less than that along the other two principal axes. In effect, the compressive tangential strain is extruding material outward in radial directions, much the same as the result achieved by squeezing a tube of toothpaste. This strain state will continue to a depth where the weight of overlying material becomes sufficient to reverse the tensile character of the radial strain.

Because of this lack of available compression to produce the required increase in density with depth, another density function will be derived as a basis for integrating the strain equations. To do this, we assume a simple variation, continuous through the second derivative, of the ratio $Y = I/Mr^2$ from its surface value of about 1/3 to its limiting value of 2/5 at the center. For any other point in the Earth, Y should have a value between these limits. With the two known values, the ratio may be stated

$$Y = 2/5 - 1/15\, X^2 \quad (X = r/R) \qquad (7)$$

Since the absolute variation of Y is small, this function may be used if it is in reasonable agreement with other facts connected with the Earth's moment of inertia and density. *Jeffreys* [1952, p. 152] gives an ellipticity of about 0.00256 for the equal density layer at the core boundary. By use of the surface ellipticity and the Radau approximation, we find Y to be about 0.36 at the core boundary. Eq. (7) gives about 0.38, while Bullen's density distribution gives about 0.39.

By first differentiating the equation $Y = I/Mr^2$ with respect to r, we get

$$3\int_0^r \rho r^2\, dr = \rho F \qquad (8)$$

where $F = r^3(2 - 3Y)/(Y' + 2Y)$. Further differentiation of (8) yields

$$\rho' + \left(\frac{F'}{F} - \frac{3r^2}{F}\right)\rho = 0 \qquad (9)$$

Eq. (9) may be solved, using (7) for ρ. To evaluate the constant of integration, we call upon the known average density of the Earth. The particular solution of (9) is

$$\rho = \frac{2053(3 - X^2)}{(4 + X^2)^{4.5}} \qquad (10)$$

Densities at various radii as determined from (10) are:

$\frac{r}{R}$	1.0	0.8	0.6	0.4	0.2	0
ρ	2.94	4.86	7.20	9.58	11.63	12.05

As in the case of the primary seismic wave curve, this density distribution can be approximated by simple functions for each zone in the Earth. The zones used for integration of the several sets of equations are those established by Bullen, based on the characteristics of the seismic velocity distribution.

Solutions of the equilibrium equation—With the foregoing relations, it is now possible to make the appropriate substitutions in the equilibrium equation and solve for u, u/r, and u'. Boundary conditions determining the value of the integration constants are: (a) at the surface, $\phi = 0$; (b) at

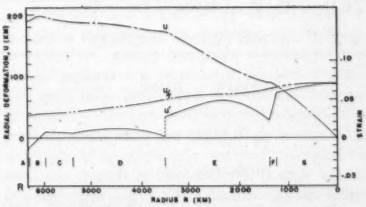

FIG. 2 – Radial deformations u, tangential strains u/r, and radial strains (u') in the Earth; designation of zones after Bullen

each zonal boundary, u (zone X) = u (zone Y), and ϕ (zone X) = ϕ (zone Y); (c) at the center, u = 0 and $u' = u/r$.

No significant strained density jump at the core boundary is assumed for this study. Instead, the discontinuity in velocity of the seismic wave at this locus is taken to be attributable to the different radial strains and different compressional moduli of the mantle and core material.

We obtain as particular solutions of the equilibrium equation the following expressions for u, the radial deformation, in terms of R (the outer radius), at any radius $r(X = r/R)$.

In Zone A: $1 \geq X \geq 0.9948$, $P = 6.50 \times 10^5$ cm/sec, $S = 3.74 \times 10^5$ cm/sec, $g = 980$ cm/sec^2

$$u/R = -0.3694X^2 + 0.5056X - \frac{0.1067}{X^2} \quad (11)$$

In Zone B: $0.9948 \geq X \geq 0.94$, $\rho = 8.46$ (1.35 $-$ X) gm/cm^3, $P = 21.80$ (1.35 $-$ X) $\times$ 10^5 cm/sec

$$u/R = -0.132\left\{0.25 + \frac{0.675}{X} + \frac{1}{X^2}\left[0.8644 \log_e(1.35 - X) + \frac{1.1038}{1.35 - X} + \frac{1.23X - 1.6177}{(1.35 - X)^2} - 0.2386\right]\right\} \quad (12)$$

In Zone C: $0.94 \geq X \geq 0.85$, $\rho = 10.3$ (1.27 $-$ X) gm/cm^3, $P^2 = 529$ (1.10 $-$ X) $\times$ 10^{10}

$$u/R = -0.008266X^3 + 0.016635X^2 + 0.011802X - 0.004521 - \frac{0.012415}{X} + \frac{1}{X^2}[0.006622 \log_e (1.10 - X) - 0.023413 \log_e (1.27 - X) + 0.011627] \quad (13)$$

In Zone D: $0.85 \geq X \geq 0.548$, $\rho = 11.80$ (1.21 $-$ X), $P^2 = 3190R$ (1.49 $-$ X)

$$u/R = -0.13622\left\{0.20X^3 - 0.2245X^2 - 0.2084X - .03465 - \frac{0.10116}{X} - \frac{1}{X^2}[0.13415 \log_e (1.49 - X) + .01096 \log_e (1.21 - X) - 0.038036]\right\} \quad (14)$$

In Zone E: $0.548 \geq X \geq 0.219$, $\rho = 10.97$ (1.261 $-$ X), $P^2 = 2105R$ (1.03 $-$ X)

$$u/R = -0.0320X^3 + 0.0704X^2 + 0.0587X + 0.01897 + \frac{0.01211}{X} + \frac{1}{X^2}[0.1637 \log_e (1.03 - X) - 0.185 \log_e (1.261 - X) + 0.03825] \quad (15)$$

In Zone F: $0.219 \geq X \geq 0.197$, $\rho = 11.63$, P = $47.7X \times 10^5$

$$u/R = -0.009845X + \frac{0.00858}{X} - \frac{0.001106}{X^2} \quad (16)$$

In Zone G: $0.197 \geq X \geq 0$, $\rho = 11.91$, $P = 11.26 \times 10^5$

$$u/R = -0.10651X^3 + 0.070766\,X \quad (17)$$

These functions are shown graphically in Figure 2. Of significance are the following deformations and strains:

(a) The locus of maximum radial shortening (197.5 km) is at a depth of about 268 km. Relative to this locus, material nearer the surface is displaced outward from the center, even though the absolute displacement is inward.

(b) The surface radial displacement is some 188 km, corresponding to a great circle contraction of about 1181 km.

(c) The hydrostatic compressive strain at the center has a value of 0.07077. This strain is accompanied by a hydrostatic pressure of 3.206 megabars.

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Radiation Damage in Zircon and Its Relation to Ages of Paleozoic Igneous Rocks in Northern New England and Adjacent Canada

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Abstract—A study of radiation damage in zircon from 42 igneous rocks (mostly granites) from northern New England and adjacent Canada has been made, using x-ray diffractometer measurements to determine unit cell dimensions and alpha counting to determine the activity, or rate of damage to the crystal structure. From previous work changes in c_0 (unit cell vertical axis) are known to be proportional to changes in dosage (alphas/mg of sample). The ratio dosage/activity is a measure of the time involved. This ratio corresponds, within experimental error, to ages already determined for many of the rocks used in the present study (Pb-α method for zircon and Sr-Rb method for biotite). Other ratios are invariably low. This feature is discussed in terms of the processing of samples needed to obtain the lowest possible activity. Fine grinding, close magnetic separation, and aqua regia treatment tend to eliminate surface concentrations and isolated internal clots of radioactive material, the chief causes of high activity and low age ratios. Where, after adequate processing of this kind, ratios are still low relative to standard age determinations, it is suggested that the ratio represents the date of a later metamorphism.

Introduction—Radiation damage in minerals has been investigated for many years. There is an extensive literature, recently summarized by *Rankama* [1954]. Its most spectacular feature is the development of halos around radioactive nuclei, best known in biotite of salic igneous rocks. The work of *Henderson* [1934] and his associates on these external manifestations of radiation damage is a classic of its kind. Internal aspects of radiation damage, shown in varying degree by changes in physical properties of zircon, sphene, allanite, etc. are also well known. *Holland* and *Kulp* [1950] suggested that measurement of radiation damage in such minerals could be used as an independent age method. Attention has since been directed particularly to zircon because of its widespread occurrence as an accessory mineral and because it retains in its crystal lattice, better than other radioactive minerals, the evidence of the degree of damage caused by alpha-particle bombardment.

The writers were first attracted to this field because of its possibilities in establishing time markers in non-igneous as well as igneous rocks. Zircon is an extremely stable detrital in sediments and is believed to persist without important recrystallization through the lower grades of metamorphism. Not infrequently two or more types of zircon, distinguishable by crystal habit or color, occur in gneisses and migmatite. Such occurrences pose challenging problems. As a first approach to their solution an independent calibration must be provided to relate the amount of radiation damage with time. Igneous rocks offer the best opportunity for this since, by a variety of independent analytical methods, the age not only of zircon, but of other coexisting minerals such as biotite and muscovite can now be uniquely determined.

The writers [*Hurley* and *Fairbairn*, 1953] made a preliminary study, using x-ray diffraction and alpha-activity measurements, of the amount of damage in zircon from igneous rocks of various ages, but were unable with the material at their disposal to establish a satisfactory relation between dosage (α-disintegrations per mg of sample) and damage (measured by change in $\{112\}$ lattice spacing). *Holland* and *Gottfried* [1955] have now made a highly significant contribution to the problem, also using X-ray diffraction and alpha activity measurements, but with the advantage of much more critical sample material. Gem quality zircon from Ceylon was used which proved to have essentially concordant age (570 ± 20 on 17 specimens by Pb-α method; 540 ± 20, U238/PB208; 544 ± 20, U235/Pb207; 555 ± 20, Pb207/Pb206; 538 ± 20, Th232/Pb208) as well as a wide range of alpha activity. It was therefore possible to establish dosage-damage relations with considerable precision and over a satisfactory range. Figure 1 is a plot of the working curve obtained by Holland and Gottfried, and of that later obtained by the writers (our curve is based on a selection of samples generously contributed by Holland, but on fewer data). The agreement is within experimental error. It was found that the dosage-damage plot was linear if c_0 of the unit cell was computed to represent degree of damage (for dosage values less than $300\alpha/\text{mg} \times 10^{13}$, which is also the range of practical usefulness of the method; a_0, which gives a non-linear relation, was not used).

This dosage-damage ratio has recently been

tested by *Holland* [1955] on pegmatitic and accessory zircon of known age, using the relation

$t = (D/\alpha)\psi$ where

t = time in millions of years (m y)
D = radiation dosage in α/mg
α = activity in α/mg yr
ψ is a function of D/α and the Th/U ratio in the sample

The range of Th/U in zircon is between 0 and 2 and, where granitic rock is the host, is usually less than 1 [*Hurley* and *Fairbairn*, 1953]; Figure 2 shows that ψ is little affected by changes in Th/U of this magnitude.

Holland has set forth the conditions which must be met in order to use the above equation for age measurement. (1) Adequate precision in measurement of unit cell dimensions and alpha activity must be attained. This is easily achieved with present equipment if the radiation dosage is not greater than 300α/mg ($\times 10^{13}$). (2) At the time of its crystallization the unit cell of the zircon unknown must be identical with that of the completely undamaged Ceylon zircon. Annealing tests by Holland showed this to be so for all practical purposes. (3) The characteristics of the dosage-damage relation of the zircon unknown must be the same as that shown by Ceylon zircon. It was found that this condition is met if changes in c_0 of the unit cell are used to determine radiation dosage. Changes in a_0 are anomalous. (4) Subsequent to its crystallization, no physical or chemical change is permissible in the zircon unless related to normal radioactive decay and falling temperature. Chemical changes should not be difficult to detect if suitable annealing and analytic tests are carried out. Temperature changes in the rock sufficient to anneal zircon are more difficult to assess and will be treated at another place in this paper.

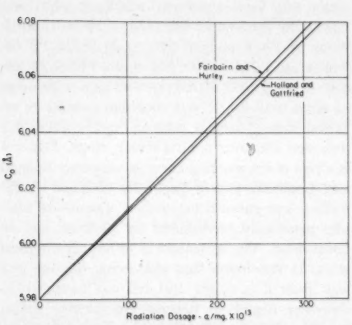

FIG. 1 – Linear relation between length of c_0 and magnitude of radiation dosage for zircon (for dosage greater than 300α/mg $\times 10^{13}$ this relation is non-linear).

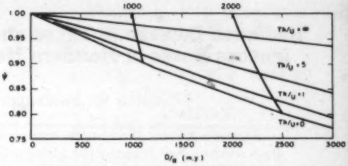

FIG. 2 – Relation of ψ (function of D/α and Th/U) and D/α (radiation dosage/activity) for zircon with a range of Th/U values

Holland's tests of the radiation damage method, made on zircons of widely varying age and environment, in general either agree with ages independently determined by other methods, or are low. In view of the conditions for successful performance by the radiation damage method just outlined, all criteria would seem to have been met where agreement is found; for the low values, there might have intervened either some post-crystallization event such as thermal metamorphism, or, the processing of the zircon prior to measurement may not have been complete. Holland suggests the former of these alternatives in explanation of certain low values he obtained, but lacks adequate field evidence in support of the idea. (Laboratory annealing tests by Holland on these zircons at 550°C (dry), for 24 hr, showed partial restoration of the structure for some, and essentially no change for others. Assumption of a post-crystallization metamorphism for the latter apparently conflicts with geological evidence. As Holland states, however, tests of such short duration may not be conclusive.)

Present investigation—The primary aim of the present investigation was to test with some thoroughness the time relation of radiation damage in zircon of Paleozoic igneous rocks either against known stratigraphic position, or against an age fixed by the time of crystallization of zircon or mica, or against both. To this end concentrates of zircon were obtained from 42 igneous rocks, mostly granites, from localities in northern New England and adjacent Canada. Many of these have no known critical field relations; for others the biotite and muscovite ages are not yet completed. Nevertheless, enough has been accomplished to warrant a progress report, the success

of which can be judged from the tables and text which follow.

Processing of samples for radiation damage measurement—The problem of low radiation damage ratios raised earlier cannot be explained as metamorphic unless measurements have been made on adequately processed material. The need for this will become apparent from the following.

After considerable trial and error, the most satisfactory procedure for preparation of zircon samples for radiation damage study was found to consist of the steps in Table 1. In processing granites [*Fairbairn*, 1955] the most probable impurities remaining with the zircon concentrate (after all quartz, apatite, etc. are eliminated) will be pyrite (dissolved in boiling HNO_3), barite (removed by treatment with Na_2CO_3), fluorite (decomposed by H_2SO_4), and topaz (separated in Clerici solution). If the zircon crystals appear to be homogeneous, a magnetic separation is made at the lowest tilt which yields a non-magnetic fraction large enough for the remaining steps. This angle, with closely sized zircon, may be as low as one degree.

The grinding and screening are carried out in acetone. To avoid undue loss of sample as fines, grinding is interrupted frequently, the product washed through a 400-mesh screen, and the oversize returned to the mortar. The ground zircon, with fines removed, should flow evenly through the Frantz separator, again using the lowest tilt commensurate with a non-magnetic fraction of adequate volume.

The need for this procedure is primarily to obtain a sample having the lowest possible activity. Activity measurements on whole samples (no magnetic concentration or aqua regia treatment) may in some cases be almost twice as high as the value obtained after processing. Table 2 shows an example of this, together with data on the U, Th, and Pb content of various magnetic fractions.

TABLE 1 – *Table showing sequence of operations in preparation of zircon for radiation damage investigation*

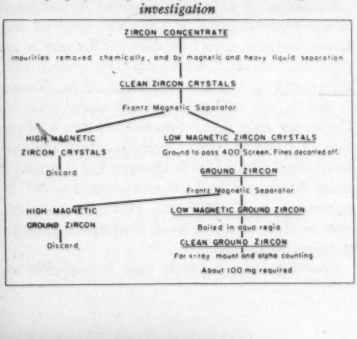

TABLE 2 – *Correlation of magnetic properties, radioactivity, and U, Th, Pb content with radiation damage ratios for an eastern Massachusetts Zircon (Cape Ann)*

Sample	Relative magnetic susceptibility	U ppm	Th ppm	Pb ppm	Activity α/mg hr	Pb-α age m y (Webber)	Radiation damage ratio
3005 A	High	2765	1890	140	1225	290	100
B	Medium	2270	1200	85	960	230	130
C	Low	1320	740	58	560	265	215
3005	No magnetic separation	...	...	...	810	...	145

Within experimental error, it is seen that the Pb-α age measurement is unaffected by these changes. The dosage/activity ratio in zircon is, on the contrary, highly sensitive to these factors.

In non-metamict zircon, with which we are concerned here, there are probably two reasons for this: (1) the concentration of U and Th at the surfaces of the crystals, and (2) the occurrence of scattered clots of radioactive material within the grains. Acid treatment, grinding, and magnetic separation remove in large part these two sources of high alpha-activity whereas measurements of the unit cell, reflecting the overall damage, will not be sensibly affected by any of these operations. To obtain a significant dosage/activity ratio it is therefore essential either that the activity of the whole crystals initially be low (about 100 α/mg) or that enough zircon be available for the processing indicated in Table 1, so that a least-magnetic fraction may be obtained with the Frantz separator. The strongest confirmation of this reasoning and procedure is the accord obtained with the Pb-α ages for the younger group of Massachusetts granites (Table 3). Low radiation damage values in the other tables, insofar as a metamorphic origin is not suspected, are usually from small samples where adequate magnetic processing was impossible.

X-ray examination—The mounts for x-ray study are made by fine-grinding a few milligrams of the final product of Table 1 and then mixing it with a somewhat smaller quantity of finely powdered silicon as an internal standard. A glass disc which fits the head of a Norelco specimen rotating device is used, with collodion and amyl acetate, to bond

TABLE 3 – *Eastern Massachusetts zircon data, 250 m y age group; granites only*

No. and locality	Radiation dosage α/mg. $\times 10^{12}$	Activity α/mg hr	Radiation damage ratio, minimum age, m y	Pb-α age m y (Webber)	Comments
3004 Peabody	36 ± 5	135	275	270 ± 20	Difference +2%
3006 Cape Ann	62 ± 6	270 ± 20	255 ± 30	250 ± 20	Difference +2%
3051 N. Attleboro	94 ± 4	500	200	225 ± 25	Difference −9%
3052 N. Attleboro	137 ± 12	630	240	220 ± 22	Difference +9%
3107 Whitinsville	86 ± 3	375 ± 28	255 ± 21	270 ± 30	Difference −6%
3013 Uxbridge	62 ± 1	310 ± 22	220 ± 16	230 ± 22	Accord with Sr-Rb biotite age of 234 m y
3005 Cape Ann	108 ± 4	560 ± 40	215 ± 17	260 ± 25	Insufficient zircon for adequate tests of activity and damage
3011 Leominster	38 ± 3	226	185	230 ± 25	

the mixed zircon-silicon powder. The tapering edges of the dried mount are removed before mounting in the rotating holder.

Scanning, recording, and measuring are carried out essentially as described by *Holland* and others [1955] except that Fe radiation is used and only two sets of peaks, {200} and {112}, are used for determination of c_0 and a_0 (for d_{112} and d_{200} ($= a_0/2$), the general expression for c_0 (tetragonal) $= l/\sqrt{1/d^2 - (h^2/a^2 + k^2/a^2)}$ reduces to $2/\sqrt{1/d^2 - 2/a^2}$)

The special sedimentation cell used by Holland for preparing mounts gives potentially more precise x-ray data than others in common use and the extra time and effort demanded appears justified in setting up the basic damage-dosage relation shown in Figure 1. However, for most work with accessory zircon, tests in our laboratory indicate that ordinary mounts using the rotation device give adequate precision, particularly in view of the problem of variable alpha activity just discussed.

Alpha counting—The alpha counts were made with the same equipment as used for the Pb-α age ratios determined by *Webber* and others [1956]. Ground zircon samples prepared as outlined (see Table 1) were measured for alpha-particle emission from a thick source. In calculating the alpha activity in α/mg hr within a sample of material, from the measured alpha emission in α/cm^{2}hr from a thick source of the sample in a counter of known geometry, it is necessary to know both the absorption factor and the lower limit of alpha energy that will be recorded by the alpha counter. A source absorption factor for zircon was calculated to be 0.493 by the method described by *Nogami* and *Hurley* [1948]. In this calculation it was assumed that all alpha particles emerging from the sample would be counted if they had a residual air range exceeding 0.5 cm.

A correction factor of 1.06 is also applied, determined by plotting the alpha activity determined by alpha count, against the alpha activity calculated from separate uranium and thorium measurements using the scintillation spectrometer. Although the precision of these scintillation spectrometer measurements is poor, owing to small sample size, the absolute accuracy of the method is preferred over the calculated absorption factor and efficiency used in the determination of alpha activity from total alphas counts. This adjustment of six per cent is, therefore, applied as an efficiency correction for the counter.

Estimation of experimental error—An estimate of experimental error is given for most of the dosage/activity ratios. Implicit throughout is an unknown, but small, additional error arising from uncertainty in the dosage-damage curve (Figure 1) and in the calibration of the alpha counter. The dosage error is based on the fact that a difference of 0.005 in {200} (corresponding approximately to 0.01 in {112}) changes the dosage by about fifteen per cent. Therefore, in any set of measurements of {200} and {112} the standard error of their means is used to compute a corresponding dosage error.

Counting error in single runs is negligible as

the number of counts is in excess of 3000. Replicate runs (three or more) give some spread as shown by the estimates given after some of the values. The calculated total error in the dosage-activity ratio is for the most part well under ten per cent. Allowing for slight unknown error in the slope of the dosage-damage curve and for shortcomings in calibration of the alpha counter, an overall experimental error of ten per cent is a likely estimate.

Eastern Massachusetts zircon—Webber and others [1956] have recently completed an age investigation of eastern Massachusetts granites, using accessory zircon and the Pb-α method. Two age groups centering around 360 and 250 m y emerged from this study. Comparable radiation damage data are now available, as shown in Tables 3 and 4. For the 250 m y group (Table 3) the radiation damage time interval checks within ten per cent of the Pb-α age and may be considered to represent 'true' ages for these rocks. One independent check (a Sr-Rb biotite age) is included in the table. For the 360 m y group (Table 4) this concordance is lacking. Confirmation of the greater age of these granites if afforded by an age determination of biotite (Sr-Rb) in one sample (322 m y); nevertheless the radiation-damage time interval is well under 300 m y and is in the age range of the younger granites of Table 3. As enough zircon for adequate processing was available in three of the four samples, the writers suggest that this is evidence of thermal action on the zircon in the older granites caused by intrusion of the nearby, later granites. The radiation damage time interval of the zircon in these older granites therefore dates from a later zero point and does not give the true age of the rocks. It does however give the general date of the last high-temperature metamorphism which affected them. It need hardly be emphasized that in its own way this is also important as a time marker in geologic dating.

Additional data, not readily comparable with the previous radiation damage ratios, are shown in Table 5. The genesis of the finely gneissic two mica granite from the Fletcher quarry, West Chelmsford, has been a source of some argument [*Currier* and *Jahns*, 1952]. The zircon concentrate shows some rounding of crystal faces, a feature not observed in any other zircons reported in this paper. The high Pb-α age stands alone among the Massachusetts granites determined by this method. Given sufficient zircon for magnetic processing, the activity might have been halved and the radiation damage ratio doubled, to give a value of about 180. The Pb-α ratio would nevertheless still be threefold greater. This is obviously a highly interesting granite and a further report will be made when age data on its biotite and muscovite are available.

The Hoppin Hill granite has latterly been considered Precambrian [*Dowse*, 1950], based on critical field relations in one locality. A roadside sample a few hundred yards from the critical outcrop unfortunately had too little zircon for Pb-α analysis and for adequate radiation damage study. Nevertheless, if magnetic processing had yielded a sample with as little as one-half the given activity, the radiation damage ratio would still indicate a Paleozoic age for the granite (about 200 m y). As no mica is available in the sample (for Rb-Sr analysis) the Hoppin Hill problem is still unresolved.

The Dedham sample seems definitely to be Precambrian. If magnetic processing of a larger concentrate of zircon showed any change in activity, our experience indicates that it would be downward, thus increasing the ratio. Additional work on granites in this vicinity, including Sr-Rb analysis of mica, would be highly desirable.

Nova Scotia zircon—A study of biotite and mus-

TABLE 4 – *Eastern Massachusetts zircon data, 360 m y age group, granites only*

No. and locality	Radiation dosage α/mg $\times 10^{13}$	Activity α/mg hr	Radiation damage ratio, minimum age m y	Pb-α age m y (Webber)	Comments
3012 Milford	72 ± 3	340	235	375 ± 35	Difference −37%; Biotite age (Rb-Sr) is 322 m y
3106 Milford	86 ± 8	590 ± 39	160 ± 18	340 ± 30	Insufficient zircon may explain low radiation damage ratio
3014 Wrentham	87 ± 9	490 ± 37	200 ± 26	365 ± 35	Difference −45%
3105 Wrentham	95 ± 3	378	280	370 ± 35	Difference −24%

TABLE 5 – *Eastern Massachusetts zircon data, miscellaneous granites*

No. and locality	Radiation dosage α/mg $\times 10^{13}$	Activity α/mg hr	Radiation damage ratio, minimum age m y	Pb-α age m y (Webber)	Comments
3108 Chelmsford	60 ± 2	830	80	480 ± 51	Some rounding of crystals; insufficient sample
3050 Hoppin Hill	43 ± 4	460	100		Insufficient zircon
1982 Dedham	89 ± 4	181	540		Insufficient zircon

TABLE 6 – *Nova Scotia zircon data; all granites except as noted*

No. and locality	Radiation dosage α/mg $\times 10^{13}$	Activity α/mg hr	Radiation damage ratio, minimum age m y	Biotite age (Rb-Sr) m y	Comments
2090 Halifax	63 ± 4	225 ± 1	310 ± 20	380	Difference −22%
2092 Port Mouton	58 ± 1	240	270	...	...
2094 Atwood's Brook	50 ± 2	166 ± 1	335 ± 15	...	...
2097 Springfield	63 ± 1	260 ± 3	270 ± 5	350	Difference −23%
2098 New Ross	58 ± 1	221 ± 6	290 ± 9	360	Difference −20%
2099 Lake Gaspereau	66 ± 2	225	320	355	Difference −10%
2096 Albany Cross	67 ± 2	264	280	335	Insufficient zircon; Difference −16%
2091 Shad Bay	52 ± 2	385	155	385	Insufficient zircon
2089 Queensport	51 ± 3	418	140	370	Insufficient zircon
2093 Birchtown	73 ± 3	530	185	...	Quartz diorite; may not be comparable with granite ages

TABLE 7 – *Maine, Quebec, Vermont zircon data, 305–355 m y group, granites except as noted*

No. and locality	Radiation dosage α/mg $\times 10^{13}$	Activity[a] α/mg hr	Radiation damage ratio, minimum age m y	Comments
3058 Sprucehead Island, Me.	63 ± 3	233	305	...
3061 Moosehead Lake, Me.	42 ± 1	153	305	Kineo rhyolite, Early Devonian
3041 Brattleboro, Vermont	60 ± 2	218	310	Post-Middle Ordovician; biotite age (Rb-Sr) is 310 m y
3085 Deer Isle, Maine	55 ± 1	187	325	Neighboring Vinalhaven granite, believed to be comagmatic, intrudes middle Silurian volcanics and sediments
3065 Mt. Megantic, Quebec	94 ± 3	318	325	...
3066 Scotstown, Quebec	93 ± 5	291	355	Post-Middle Ordovician

[a] No replicate runs were made but, as conditions were identical with runs in Tables 3–6, the range of experimental error may be assumed to be equivalent.

TABLE 8 – *Maine, New Hampshire, New Brunswick zircon data, 160–250 m y, all granites*

No. and locality	Radiation dosage α/mg × 10^{13}	Activity[a] α/mg hr	Radiation damage ratio, minimum age m y	Comments
3078 Calais, Me.	147 ± 9	839	195	These granites, all from the Passamaquoddy Bay area, are believed to be comagmatic. They intrude middle Silurian strata and are overlain by late Devonian. The low-activity sample 3136 probably gives the best radiation damage ratio
3135 D'Eauville's Head, Me.	144 ± 22	810	200	
3136 Oak Bay, N. B.	30 ± 1	133	250	
3126 Conway, N. H.	99 ± 5	540	205	Sr-Rb biotite age is 170 m y
3062 Jackman, Me.	39 ± 1	176	245	Intrudes early Devonian sediments
3064 Mt. Pleasant Camp, Me.	117 ± 5	829	160	
3077 N. W. of Fredericton, N. B.	76 ± 4	515	165	
3055 Hallowell, Me.	85 ± 6	540	175	Insufficient zircon for adequate processing; minimum ages only
3080 Mt. Desert, Me.	115 ± 9	728	180	
3063 Rangely, Me.	59 ± 1	343	195	

[a] See footnote to Table 7.

covite in Nova Scotia granites is now under way in our laboratory, using Sr-Rb and K-A as independent methods of age determination. The work already completed, however, is sufficient for preliminary comparison (Table 6). Inspection of the table shows the radiation damage values to be smaller than the biotite ages; the deviation (between 10 and 22 pct) is on the whole greater than the estimated experimental error, and might be interpreted as an indication of post-magmatic thermal metamorphism.

The relatively close accord of the radiation dosage values and of the activity values in Table 6 is a matter of considerable interest, although without any geological correlation possible as yet. U and Th determinations for six of these rocks are likewise in reasonably close accord (unpublished data of Hurley). Until further data for the entire area are available, indicating the co-magmatic character of the granites, discussion of the above would be pointless.

Zircon from Maine, Quebec, Vermont (305–355 m y group)—The source rocks for the zircon in this group (Table 7) are widely scattered in northern New England and adjacent Quebec. As the activities are relatively low and enough zircon was available for complete processing (Table 1) it is believed that the radiation damage ratios will approach the biotite ages very closely when these are completed. Support for a co-magmatic province for the five granites may possibly be inferred from the relatively small range of the dosage values and of the activities (Table 6). Field relations of four of the rocks indicate that the radiation damage ratios are of the right order of magnitude. Biotite and zircon ages agree for the Brattleboro locality. The Kineo rhyolite is of particular interest because of its position in Early Devonian strata. Until complete biotite ages are available, however, the full significance of this group of ratios cannot be finally evaluated.

Zircon from Maine, New Hampshire, New Brunswick (160–250 m y group)—The source rocks for the zircons included in this section are widely scattered and are not necessarily related in age. In the first group of three (Table 8), believed to be co-magmatic, the sixfold greater activity of the first two relative to the third is a conspicuous feature. Our experience with the radiation damage method would place most weight on the Oak Bay ratio, where both dosage and activity are relatively low. The agreement of this ratio with 3062 (Jackman, Me.) where the granite intrudes early Devonian sediments is of considerable

TABLE 9 – *Provisional radiation damage—stratigraphic relations from four critical localities*

Early Devonian	Middle Devonian
305 m y, Kineo rhyolite (Sample 3061), enclosed by early Devonian strata[a]	245 m y, Jackman granite (Sample 3062), intrudes early Devonian
325 m y, Deer Isle granite (Sample 3085): based on equivalence to Vinalhaven granite, which cuts middle Silurian volcanics and sediments	250 m y, Oak Bay granite (Sample 3136), post-middle Silurian and pre-late Devonian (vicinity of Calais)

[a] Early Devonian glauconite (Carlisle Center formation, New York) is 320 m y, according to Cormier (unpublished MIT thesis, 1956).

interest, as the ratio for the early Devonian Kineo rhyolite (Table 7) was somewhat larger. A provisional tabulation of the radiation damage and stratigraphic relations is shown in Table 9.

The remaining ratios in Table 8 represent 'minimum ages' only, as the volume of the zircon concentrate was too small for adequate processing. Mica ages will later be available for these rocks.

Conclusion—In an igneous rock the radiation damage ratio either represents the time since crystallization of the zircon, or is less. If less, metamorphic dating is a distinct possibility, as suggested for some of the Massachusetts granites (Table 4), and for the Nova Scotia granites (Table 6). If the activity of unprocessed crystals proves to be low (for example, $<100\ \alpha$/mg hr), as little as 50 mg of zircon will be adequate to compute a ratio, since tests on low-count zircon have shown that magnetic splitting and acid treatment result in inappreciable change. For higher activities, however, the radiation damage ratio is of little significance unless the sample is first processed as outlined in Table 1 and the activity is determined on a least-magnetic, acid-treated fraction. For this case several hundred milligrams of zircon crystals may be required in order to obtain a final, ground sample of adequate volume.

Radiation damage ratios are most significant if comparison is possible with age data by independent methods either on zircon or on other minerals in the same rock. The ratio will unfailingly give a 'minimum age,' which is not without merit, but its final interpretation rests on other age measurements of coexisting minerals.

The writers are of the opinion that the present study justifies further exploratory work, particularly in cases where age investigations of other minerals by standard analytical methods are possible. It is sometimes forgotten that the field of geochronology has a broader potential than the mere dating of magmatic crystallization (for example, age of biotite in a granite) or determination of the time of deposition of a sediment (for example, age of glauconite in a siltstone). Dating of pre-crystallization and post-crystallization events could lead to highly significant conclusions in igneous petrology; sediments likewise, in their detritals, offer evidence of significant predeposition events which could possibly be dated. The realm of metamorphism, for both igneous and sedimentary rocks, offers an obvious extension for dating methods. In this wider field, still virtually untouched, radiation damage studies of zircon should make important contributions.

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Report of the Committee on Snow, 1955–1956

R. A. Work, Chairman

Dean B. Bogart, Robert D. Elliott, J. van de Erve, Eric Hinton (deceased), Walter E. Johnson, Gordon J. R. Kidd, M. W. Nelson, Vincent J. Schaefer, Calvin C. Warnick

The following report has been prepared by the Committee from a questionnaire sent to individuals and agencies active in snow research.

M. M. Atwater (U. S. Forest Service, Alta, Utah)—The current snow project at Alta with most application to runoff is the Snow Temperature-Snow Settlement Study which is just completing its first season. Our objective is to be able to monitor the internal stabilization of the snowpack. From the standpoint of runoff, this study should yield valuable information on compaction and hence the rate of snow melt. The equipment is simple and would be adaptable to installation on a snow course. It consists of a nichrome resistance wire suspended vertically in the snowpack. Sliding plates are attached to the wire periodically so that they are carried downward by snow settlement. The plates are connected to a junction box by wire leads where the location of each plate in relation to the ground can be established by means of a Wheatstone bridge. A thermistor is also attached to each plate so that settlement and snow temperature can be determined without digging a pit. The same meter can be wired to read both temperature and settlement.

F. S. Brown (Corps of Engineers, Portland, Oregon)—The program is to determine by aerial reconnaissance the areal coverage of snow during the melt season. The basins being investigated by the Seattle District are the Kootenai above Libby, Montana, and the sub-basins of the Flathead river at Columbia Falls, Montana. Data on areal coverage in the Kootenai basin are available for 1951, 1952, 1954, 1955, and 1956. In the Flathead basin surveys were made in 1945, 1954, 1955, and 1956. A series of three or four flights during the snow-melt season is considered desirable. On the Flathead basin, flights are made over the main valleys of the Middle and South Forks, and the main basins above the gaging station near Columbia Falls. In the Kootenai basins the flights are made over the main valley above Libby to the Vermilion River, and major tributaries such as White, St. Mary, Bull, and Elk rivers.

Four basins are being investigated by the Walla Walla District: the Clearwater, Salmon, Payette, and Boise, with incidental data being collected for the Weiser. From three to five flights are made over the basins each melt season, depending upon the conditions. The first flight is usually made sometime between March 15 and the first week in April, although it may be as late as May. The other flights are made at more or less regular intervals, with one flight being timed to coincide as nearly as possible with the peak runoff.

In 1954, the Portland District in cooperation with the Snow Investigations Unit conducted a series of flights over the North Santiam basin above Detroit Dam. These surveys were made as nearly as possible on the first and 15th of the month so that data could be utilized in conjunction with data from snow course surveys. No surveys were made during 1955 or 1956.

It is believed that when sufficient data have been collected they will be valuable in improving forecast of volume of runoff to be expected, and short term discharge forecasts.

J. H. Doughty-Davies (Water Rights Branch, Department of Lands and Forests, Victoria, B. C.)—The snow surveys have expanded from the Columbia, Kootenay, and Okanagan River basin to include the Fraser River basin. The runoff for the Fraser River at Hope is now forecast. This brings the total number of river runoff forecasts to sixteen. A study of the characteristics of the runoff for the Columbia River at Birchbank was made. A study of the relationship between area and elevation for the various major watersheds was also carried out.

The position of snow surveys within the Water Rights has been altered. It now comes within the newly formed Hydrology Section. V. Raudsepp, Senior Hydraulic Engineer, is in charge of this section. J. H. Doughty-Davies still supervises the actual snow surveys and is also a member of the Sub-committee of Ice and Snow Research of the National Research Council of Canada.

E. G. Dunford (U. S. Forest Service, Portland, Oregon)—From the Northeast, Howard Lull reports progress on snow studies in the newly estab-

lished Hubbard Brook Experimental Forest in New Hampshire's White Mountains. Periodic snow- and water-depth measurements were begun this winter in the first experimental watershed equipped for streamflow. Richard S. Sartz and George R. Trimble have prepared for publication a paper, Snow Storage and Melt in a Northern Hardwood Forest, an analysis of snow- and water-depth measurements taken in openings created by patch cuttings in sawtimber and pole stands. Depths were greater in the open, and to a lesser degree, water contents. Difference in density and melting were observed and interpreted in respect to cover conditions. At the Eastern Snow Conference, Robert Pierce reported on a region-wide study of the relation of frost and snow depth to land use and forest conditions. A paper on this subject is scheduled for publication this year.

Under supervision of Marvin D. Hoover, weekly measurements were made in the summer of 1955 of density, ablation, and aerial shrinkage at each of five alpine snowfields located east of the Continental Divide in the Front Range of Colorado. Wind, temperature, precipitation, and humidity were also recorded at each site. In addition, aerial photographs were scanned to determine the number, size, and distribution of alpine snowfields for a selected part of the Front Range at the end of September. Evaporation was computed from Light's equation and local weather data. These data were then integrated to predict the importance of late-lying snowfields on summer stream flow. The project was carried out by the Rocky Mountain Forest and Range Experiment Station in cooperation with the Research Foundation of the State University of New York. A final report is being prepared and will be submitted to the College of Forestry, State University of New York as a PhD thesis.

Snowpack management investigations in California were begun this year under the direction of the late E. A. Colman. The objective is to seek ways to improve the water yield of some nine million acres of the commercial forest zone above the Central Valley at elevations where the snow blanket lies deep, well into the dry season. Nearly 40 pct of California's stream flow is derived from this area. Tests will be made to learn how forests should be cut and other lands treated so that winter floods will be reduced, dry-season flow prolonged, and total water yield safely increased. If present prospects for cooperative assistance in this research materialize, the staff will be expanded and the other snow laboratory will be activated. Already in operation is the Teakettle Snow Laboratory, in the Kings River basin. The other is the Central Sierra Snow Laboratory, in the headwaters of the Yuba River. A paper, Forest Cover Effects on Snowpack Accumulation and Melt, Central Sierra Snow Laboratory, by Henry W. Anderson was published in the June, 1956, issue of the *Transactions*.

R. D. Elliott (North American Weather Consultants, Goleta, California)—The President's Advisory Committee on Weather Control released on February 9th an interim report stating that their evaluations of five long duration West Coast cloud seeding projects have shown precipitation increases ranging from 9 to 17 pct. To those interested in snow it is important to note that three of the five successful projects were directed toward increasing snowpack in mountain watersheds.

The Committee is cognizant of the favorableness of the western mountain terrain configurations and winter climate to the practice of cloud seeding. The Committee is also very much aware of the economic value of the snowpack with respect to both hydro-electric power generation and irrigation water supplies.

R. W. Gerdel (Snow, Ice and Permafrost Research Establishment, Corps of Engineers, U. S. Army, Wilmette, Illinois)—During the summer of 1955 SIPRE constructed experimental tunnels in the Greenland ice cap. Mining techniques were used at the ice edge near Thule and covered trenching methods used in the old firn several hundred miles out on the ice cap. These tunnels may provide protected access to the ice cap installation. Several thousand feet of tunnels were built and instrumented for deformation studies. Other research on the ice cap and in other areas in the northern Arctic included problems on visibility and white-out phenomena, radiational heat supplies and applied use of solar radiation, the blowing and drifting of snow and methods of control, production of snow compacted runways for heavy aircraft, and the supporting capacity of lake and sea ice for heavy aircraft.

At the Keweenaw Station near Houghton, Michigan, the studies on vehicular trafficability of the snow surface continues. The Transportation Corps, Research and Development Command, has constructed facilities adjoining the SIPRE laboratory in northern Michigan for a coordinated study of snow vehicle performance.

Lorne W. Gold (Snow and Ice Section, Division of Building Research, National Research Council of Canada, Ottawa, Ontario)—Our recent activ-

ities in snow and runoff have been directed primarily to our project, The Snow Survey of Canada during the past year. Analysis of the data collected from 1947 to the spring of 1955 has been completed. This study emphasized the correlation of snow-cover properties to climate. The snow survey was continued during the winter of 1955–56. In the Ottawa area the observations were made in greater detail in order to evaluate the present techniques for measuring the properties of the snow cover and to evaluate the variability of the properties in the vicinity of an observation site.

Studies were carried out on a simplified method of measuring the free water content of snow. Some observations were carried out on the behavior of snow under compressive loads. Observations during the winter of 1955–56 were made of the temperature gradient through the snow cover and the corresponding heat flow. From the data collected it is hoped that an evaluation of the thermal properties of the snow cover can be made.

During the winter of 1955–56 the Associate Committee on Soil and Snow Mechanics of the National Research Council of Canada set up a subcommittee on snow and ice. The first task of this subcommittee has been to plan the Canadian activities of snow and ice research during the IGY. Tentative proposals include (1) an expedition to Ellesmere Island, (2) mapping of the glaciers in the Canadian Rockies, (3) some extension of our present snow survey project.

T. J. Henderson (California Electric Power Company, Bishop, California)—Our company is continuing the use of aerial photographs of snow markers in an attempt to improve both our stream flow forecasts and our weather modification evaluation techniques. Our longest period of record from one of these markers is seven years.

This is the eighth year of our company's engagement in a weather modification program. Prior to this year we have used dry-ice pellets exclusively. This year, as an experiment, we have contracted the program out to a commercial cloud-seeding agency here in California and have changed the nucleating agent from dry ice to silver iodide. At present we are not sure which method holds the most promise in this area.

Walter E. Johnson (General Chairman, Western Snow Conference, Spokane, Washington)—The purpose of the Western Snow Conference is to provide an opportunity for individuals and organizations interested in snow and runoff problems from any viewpoint to meet and exchange information for mutual benefit. In 1955, 240 individual members living in the eleven western United States, western Canada, and Alaska comprised the Conference.

Snow and allied subjects are very important to the economic life in the arid western states, which accounts for the active interest in snow throughout the entire region. Annual meetings are held in April for the presentation of reports and papers concerning the practical application and research of snow runoff, forecast runoff, and related problems. A questionnaire was sent to our corporate membership last spring; it indicated that the greatest interest was in (1) improved methods of runoff forecasting and (2) weather modification operations and evaluations.

O. W. Monson (Montana State College, Bozeman, Montana)—Development work on a small over-snow vehicle has continued here at the Montana Experiment Station. Several State and Federal agencies have accepted our design and built similar machines. The machine is easily transportable in a half-ton pickup. Its first cost and operating cost is low.

Analysis of snow and rainfall data has been expanded in order to forecast anticipated water supply of the main river basins of Montana, together with many of the smaller streams used for irrigation purposes.

Morlan W. Nelson (Soil Conservation Service, Boise, Idaho)—We have developed improved forecasts and new uses for variables such as base flow. Plans are now being made to complete the base flow index for at least ten rivers in Columbia basin since this seems to be the best antecedent variable in use at this time.

In addition to this work basic data have been assembled on wind velocities and humidity over the desert rivers such as the Owyhee, Salmon Falls Creek, etc. The wind movement is quantitatively measured up to 10,000 ft. Early estimates indicate that this significantly affects the runoff during March and April in some years.

Gregory L. Pearson (Soil Conservation Service, Salt Lake City, Utah)—An interstate snow survey training conference at Alta, Utah attracted 107 participants during the week of January 13, 1956. Snow-survey conferences of this character for field personnel are sponsored by the Soil Conservation Service in even-numbered years. Safety, efficiency, and better understanding of objectives and techniques of snow surveys are included in the curricula.

R. J. Pafford, Jr. (Corps of Engineers, Omaha, Nebraska)—Corps of Engineer offices in the Missouri River basin have conducted coordinated snow surveys of the water equivalent of the plains

snow cover each spring since 1948. These surveys are not made on predetermined dates, but are scheduled a few days in advance to attempt to measure the plains snow cover near the time of maximum accumulation and occurrence of any significant melting. Repetitive snow surveys are often necessary due to occurrence of subsequent snowstorms. Measurements are made on approximately a 50-mile grid for those areas having one inch or more water equivalent. Isochron maps and depth-area curves have been prepared for at least one survey each year. In three of the nine years of record, snowpack water equivalents in excess of six inches over local areas have been measured.

J. R. Riter (Bureau of Reclamation, Denver, Colorado)—Some work has been done in the improvement of precipitation gages and shields. The heated precipitation gage intake tube which was described in the *Transactions* in April 1955, pages 311-314, has been granted a public patent by the United States Patent Office, numbered 2,701,472, dated February 8, 1955. A seasonal storage precipitation gage patterned after the Weather Bureau's 20-foot high standpipe storage gage, within which has been incorporated a heated intake tube, was placed in service in the Eklutna Lake drainage basin at the Bureau of Reclamation's Eklutna Project, Alaska, in the fall of 1955. A description of the gage with its performance during the 1955–56 winter season awaits our Project Engineer's first visit to this installation which is scheduled for April 1, 1956.

Snow-survey data are yearly becoming more useful for analyses of snowmelt runoff at proposed dam sites and extrapolation of these data to better define maximum probable snow cover for computation of snowmelt contribution to inflow design floods. The hydrothermogram procedure of computing snowmelt runoff for areas where spring rain does not significantly influence runoff has proven successful and research in application of this procedure continues. Computation of snowmelt by an approach using melt due to turbulent heat exchange is used for areas where maximum floods result from combination rain and snowmelt. Favorable comparisons of results in computing snowpack depletion were obtained using a snowpack density and compaction curve procedure and a thermal quality of snow procedure.

For operational purposes Bureau of Reclamation makes a limited number of seasonal water-yield forecasts which utilize snow survey data among other factors, and a few day-to-day rate of runoff forecasts. Punched-card control automatic data processing machinery is being used to assist in the computation of forecasts.

The final report on the Cooperative Snow Investigations which were conducted in collaboration with the Forest Service's Rocky Mountain Forest and Range Experimental Station at the Fraser Experimental Forest, Colorado, is now being completed.

David M. Rockwood (Snow Investigations Unit, Corps of Engineers, Portland, Oregon)—As indicated in last year's report of the Committee on Snow, the Corps of Engineers' Snow Investigations Unit has concentrated its effort during 1955–56 on the preparation of a summary report, entitled Snow Hydrology, completed in June 1956. It summarizes the work accomplished under the Cooperative Snow Investigations program and is written with the view of being a reference work on theoretical and applied snow hydrology. There are a total of 12 chapters dealing with the various aspects of snow hydrology as follows: Introduction; Snow laboratory data; Precipitation and snow accumulation; Water balance in areas of snow accumulation; Melting of the snowpack; Snowmelt indexes; Areal snow cover; Effect of the snowpack condition on runoff; Hydrograph synthesis; Design flood determinations; Seasonal runoff forecasting; and Reservoir regulation. The report includes a synopsis of over ten years' research in the field of snow and presents several basic analyses heretofore unpublished. Specific developments in snow hydrology which have resulted from the work are: (1) experimental evaluation of the coefficients of snowmelt, in terms of appropriate meteorological parameters, for each of the several processes of heat transfer to the snowpack; (2) methods of applying thermal-budget indexes of snowmelt to drainage basins; (3) derivation of general snowmelt equations which are applicable to drainage basins according to their physical characteristics; (4) determination of the reliability of snow courses and precipitation gages, as related to their site characteristics; (5) evaluation of each component of the hydrologic balance in areas of snow accumulation, and application of the water-balance technique to procedures for forecasting seasonal runoff volumes; (6) experimental determination of the liquid-water-holding capacity of the snowpack and transmission of heat and water through the snowpack, with methods of application of results to basin hydrologic studies; (7) methods of synthesizing stream flow hydrographs for areas involving snow; (8) investigation of the general features of atmospheric circulation as it affects moisture and energy input to

drainage basins, and the use of upper air data in estimating snowmelt; (9) derivation of an index procedure for forecasting spring-season snowmelt runoff by use of low-elevation winter runoff.

The report contains 438 pages, 22 tables, and 72 engineering plate drawings. Copies are available free upon request to Government agencies, scientific organizations, universities, and cooperating organizations. Others may obtain a copy upon payment of $4.65, payable to the Treasurer of the United States. Requests should be directed to the Division Engineer, North Pacific Division, U. S. Army, Corps of Engineers, 210 Custom House, Portland 9, Oregon.

Milton S. Sachs (Bonneville Power Administration, Portland, Oregon)—The Bonneville Power Administration initiated studies this year to develop improved forecasts of volume inflow to Hungry Horse Reservoir through the use of the snow courses located within the South Fork Flathead drainage area. Our present procedures of forecasting the inflow to the reservoir are in main based on snow courses that lie outside of the basin, because the records of the snow courses within the basin are of short duration. It is thought that the additional years of record which have been accumulated within the basin proper should yield improved forecasts. Tests are also being made to determine if the introduction of spring evapotranspiration as one of the parameters affecting seasonal runoff would improve existing forecasting equations.

Vincent J. Schaefer (The Munitalp Foundation, Inc., Schenectady, N. Y.)—Permanent and exact replicas of snow and ice crystals may be made, using a 0.5 to 3 pct solution of polyvinyl formal (Formvar 15-95) dissolved in ethylene dichloride. The solution and base for mounting the crystals must be slightly colder than 0°C. A number of different procedures for preparing the replicas are described, including the mounting of single selected crystals, the sampling of typical precipitation at a specific period of a snow storm, the preparation of a vertical cross-section of snow resting on the ground and methods for obtaining samples of window-pane frost and of frost flowers on the surface of a lake. Methods for obtaining a record of the crystal pattern in glacial ice, the preparation of replicas in a laboratory cold chamber and the sampling of snow encountered by airplane are also described in a paper presented before the Eastern Snow Conference in February, 1956.

Fred Strauss (California Water Resources Division, Sacramento, California)—Field and supervisory personnel for snow surveys in California held their second annual meeting at Redding, California, in March 1956. Purpose of these meetings is to encourage better understanding of the snow survey program and to ensure best possible field measurements.

J. van de Erve (U. S. Weather Bureau, Sacramento, California)—The Weather Bureau has established a new River Forecast Center at Hartford, Connecticut. The procedures for forecasting streamflow take into consideration rates of melting snow.

A current project is the evaluation of degree-day and degree-hour factors, using the published hydrometeorological logs of the Cooperative Snow Investigations of the Corps of Engineers and Weather Bureau.

Snow-line aerial photographic reconnaissance in the Upper Columbia basin is continuing as an Air Forces Training Project, but will be based at Moses Lake Air Force Base, Washington, this spring (1956) rather than from Spokane. In this project many photographs are taken vertically, and obliquely to each side from cameras in various positions on the plane as a topographic mapping flight is made for several hundred miles over paths designated by the Portland River Forecast Center of the Weather Bureau. The Air Force thus makes a real contribution to this project by providing photographs of scientific value rather than photographs primarily for training only. (See also report by F. S. Brown.)

Snowfall intensity rates were required by the California State Highway Department in connec-

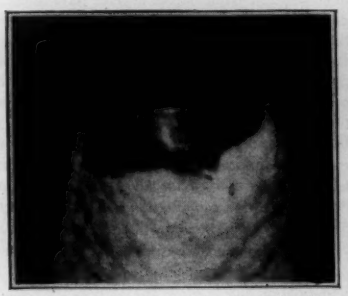

FIG. 1 – Close-up photograph of heated orifice of Sacramento storage gage showing that the snow did not accumulate on the rim of the gage; picture taken at 21h 30m, February 21, 1956; air temperature during storm remained essentially at 30°F, and at 21h 30m, February 21, the surface temperature of the orifice was 35°F

tion with the design of a new four-lane highway (U. S. 40) over Donner Pass. Present rotary snowplows cannot throw the snow far enough and high enough to clear snowbanks at the far side of four lanes plus median strip. One suggestion even was to bale the snow from the inside lanes for stacking on the median strip. In this work, water equivalents of the hourly snowfall were desired as the weight of the snow to be removed is often more important than the volume. Highway departments of the West are urged to anticipate possible highway relocations and arrange to obtain snowfall observations now, so that data for a period of years will be available when needed. Another feature of this work is the demand for frost-depth data, for computation of feasibility and costs of highway excavation and heavy grading.

Radio-isotope gages have worked well in the Sacramento Corps of Engineer District, and installation of more are planned. Location at or near a snow course with previous record is desired. There is a practical limit to the snow depth that can be measured, regardless of how large a quantity of the radio isotope is used. Capacity of some of these gages was exceeded by the heavy snowpack of the 1955–56 winter season.

Data on snowfall in remote areas as measured in the storage gage program of the Weather Bureau is being reviewed. All original records of gages operated by the Weather Bureau and cooperating agencies, State, Federal, and municipal, have been reviewed. It is anticipated that records to date will be assembled in a series of volumes, and republished for convenience of the user. Simplified observational forms for charging, recharging, and periodic interim visits have been prepared.

Work by the Corps of Engineers Sacramento District with Stanford Research Institute on radio-isotope gages is resulting in a reduction of the background count. The background count can now be cut 80 to 90 pct. Lead shields are to be installed at existing gages this coming summer.

C. C. Warnick (University of Idaho, Moscow, Idaho)—The Engineering Experiment Station of the University of Idaho is continuing its investigation of rime ice and snow capping on high-altitude precipitation gages. This investigates conditions that cause capping and a development of a heated-orifice storage gage that operates unattended through an entire winter.

The first prototype gage operated on the campus for nearly two months and is giving a very encouraging performance. This study is now supported on a cooperative basis by the following groups: Corps of Engineers, Bureau of Reclamation, Weather Bureau and the Soil Conservation Service.

Sometime this spring we will publish our Engineering Experiment Station Bulletin 10, entitled Influence of Wind on Precipitation Measurements at High Altitudes.

Figure 1 was taken during a particularly heavy snow storm when the precipitation gage would have capped if the orifice had not been heated. Moscow weather, unexpectedly, has been excellent for testing the gage this winter (1955–1956).

J. A. West (Salt River Project, Phoenix, Arizona)—The greatest interest in our watershed now, and one that is getting state-wide and national attention is a cooperative working agreement by the Salt River Valley Water Users Assn., the Arizona State Land Department, and the University of Arizona, whereby there is set in motion an intensive search for the best sort of watershed modification to bring about increased flow of our streams. Purpose of the project is as follows: Develop a plan which will (1) justify the need for an action program, (2) show the place and importance of the watershed or watersheds as a source of additional water, (3) select the water or watersheds on which there is the greatest possibility of getting an increased economic supply of water, (4) work out a plan for modification of the watershed to bring about increased flow of streams and improve range conditions, (5) determine the benefits to be derived from such modification in terms of dollar value and determine the cost that would be incurred in effecting such a plan, and finally, (6) make recommendations based upon the findings.

Specialists on watershed modification are being invited from various agencies and universities to review our problem and make recommendations.

U. S. Soil Conservation Service, 209 S. W. 5th Avenue, Portland, Oregon (R. A. W.)

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Discussion of "Report of the Committee on Snow, 1954–55"

BY ROBERT A. WORK AND OTHERS

(Contribution of P. E. Church on variations in the albedo of snow)

[*Trans.*, **36**, 1071, 1955]

Louis Lliboutry (University of Grenoble, Isère, France)—Buettner and Hubley's observations are discussed in the paper by *Hubley* [1955]. In short he says: "Old snow has a lower albedo for high angles of incidence, when melting is produced primarily by insolation rather than by warm wind." This fact is illustrated by the formation of micropenitents (that is, penitents of very little height; see Fig. 1), which can occasionally appear under all kinds of climate. I have often observed them in midwinter in the French Alps after a week of fine weather. They can have any height from a few millimeters to several centimeters. Under subtropical climates, penitents can reach several meters in height.

I have previously given an explanation of this phenomenon [*Lliboutry*, 1953, 1954, 1956]. With strong insolation and a dry, cool air, the evaporation over a smooth snowfield is considerably greater than melting, and the snow remains under 0°C. This regimen is an unstable one. In every crack of the sun crust, or even in every hole produced by the roughness of the snow deposit: (1) radiation is trapped, (2) humidity increases, (3) owing to humidity, infra-red radiation is trapped. So the temperature within the crack increases, local melting occurs, and the crack gets bigger and bigger. With the diurnal movement of the Sun, the east-west cracks deepen more than the others. Any circular hole takes an east-west elongation. As I have explained elsewhere, from several isolated little cracks or holes an entire field of micropenitents is created.

The factors which are pertinent to the formation of micropenitents and which should be measured at each hour of the day are principally: (a) insolation, (b) air temperature well above the surface (great as compared to the height of penitents), (c) dew point (better than relative humidity) at this same height, and (d) wind velocity. When there is wind, these factors must be measured at several points from the beginning of the snowfield, in the upwind direction.

If checked by experiments, the following formulas may be used. They are an approximate solution of *Sutton's* [1953] equations. These formulas, in Sutton's notation, for heat transfer to the snow by unit area and unit time, are

$$Q = \rho C_p (T_\infty - T_s) \sqrt{UK/\pi x} \qquad (1)$$

for water vapor transfer to the air by unit area and unit time

$$E = (m_s - m_\infty) \sqrt{UK/\pi x} \qquad (2)$$

The principal factors which characterize a field of micropenitents are: (e) mean height of the blades, (f) mean distance from crest to crest in a transverse (that is north-south) direction (for well-characterized penitents these are 30 to 40 pct of the mean height), (g) mean albedo of the field for sunny days is approximately that at midday, as midday hours have greater weight (for old penitents, the variation of the meridian elevation of the Sun becomes important), (h) the mean albedo of the field for totally overcast days.

The thermic balance for a field of penitents must be computed for a thick layer, which I shall call the exchange layer. Its upper limit will be a plane tangent to the higher crests of the blades, its lower limit a plane at about 20 cm under the deepest furrows, where the solar radiation becomes negligible. We can then write, per unit area and unit time

$$(1 - \alpha)i - i_r + Q = (L_f + L_e)E + L_f F \qquad (3)$$

where α = albedo for solar radiation (as pointed out in (g) or in (h) according to the cloudiness)

i = solar radiation which is direct or diffused by the clouds

i_r = net losses by infra-red radiation

Q = heat transfer from the atmosphere to the top of the exchange layer

E = evaporation from the field, that is the flux of water vapor emerging from the top of the exchange layer

F = percolation from the bottom of the exchange layer downwards

L_f, L_e = latent heats

To calculate Q and E we must know also, at each

FIG. 1 – Perfectly well-characterized micropenitents observed on the end of November, 1953, at 3400 m, near Santiago, Chile

hour of the day: (i) air temperature at the top of the exchange layer, and (j) dew point at the top of the exchange layer.

The transfer of heat, water vapor, and liquid water inside this exchange layer, from the furrows to the blades and to the outside, would be an exceedingly difficult problem of micrometeorology, so (i) and (j) need to be measured on the field.

Eq. (3) holds only if, during a 24-hr interval, not only the meteorological factors are the same, but also if the conditions in the exchange layer (especially the amount of liquid water) are the same. So the ablation can be accurately determined only in two cases: (1) exchange layer uninterruptedly soaked with water since the beginning of the observations (but in this case the micropenitents melt and disappear quickly), and (2) exchange layer wholly frozen at a moment of the day.

As a conclusion, it is most desirable that Buettner and Hubley's most interesting measurements should be made in a dry cool region with strong winter precipitation, like the Andes of Santiago or the Sierra Nevada of California, regions where well-characterized micropenitents and penitents are found at elevations of over 3000 m in winter, 3500 m in spring, and 4000 m in summer.

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Discussion of "Forest-Cover Effects on Snowpack Accumulation and Melt, Central Sierra Snow Laboratory"

BY H. W. ANDERSON

Trans., **37**, 307–312, 1956

J. E. Church (University of Nevada, Reno, Nevada)—Anderson's ideal snow-conservation forest and "Operation Snow Pack" (*Western Water News*, Aug. 1956) revive memories of *Trans.*, AGU 1940, pp. 920–25, and *Sci. Amer. Sup.* Sep. 7, 1912 (Vol. 74, no. 1914).

In 1912 while the Wagon Wheel Gap experiment was under way, I proposed the 'honey-comb' forest, timber screens on the lips of canyons and timber-line screens to accumulate and conserve the snow. In 1940 at Seattle, Charles A. Connaughton proposed a similar plan for the lodgepole-pine forests of the Rocky Mountain Forest.

Fortunately then the U. S. Forest Service was advocating selective instead of mass cutting, making possible the development of honey-comb and screen forests advocated by the Nevada Agricultural Experiment Station three decades earlier. The Station has now completed a decade-long study of the physics of snow melt. The mass operation by the State of California and the U.S. Forest Service is the last stage of a long development.

H. W. Anderson (Calif. Forest & Range Experiment Station, Berkeley, Calif; Authors closure)—Church's discussion of the paper is appreciated particularly because of his pioneering studies of forest-snow relations. The 'wall-and-step forest' which he called "Anderson's ideal snow conservation forest" was really labeled as a likely hypothesis which deserves testing. To test this and other hypotheses, including Church's 'honey-comb' forest, a cooperative program in research in snow management was started this year.

Early in the research, basic studies will be made in snow physics and forest-snow hydrology. These will be aimed at determining how to manage snow on specific slopes, aspects, and forest conditions for the specific objectives of increased water yield, delayed runoff in spring and summer, or control of flood waters and sedimentation.

The research is being conducted by the California Forest & Range Experiment Station, with the financial cooperation of the California State Department of Water Resources. The plans are for a combined State and Federal expenditure of some $500,000 over the first five years of the studies. The State considers the studies as a long-range feature of the California Water Plan. The Federal Government considers them as basic to development of rational management of the high elevation forests which are largely under its administration as National Forests.

It is interesting that only now are we making a concerted effort to test the observation and proposals advanced by Church some 40 years ago.

Reviews, Abstracts, and Bibliography

Reviews and Abstracts

MOONEY, HAROLD M., AND W. W. WETZEL. The potentials about a point electrode and apparent resistivity curves for a two-, three-, and four-layer earth, University of Minnesota Press, Minneapolis, Minn. 1956, 146 pp. + 243 loose sheets of reference curves $18.00 (text only, $4.50; curves only, $15.00).

Before publishing his analysis, by the Kelvin image method, of the flow of electricity in a layered earth, *Hummel* [1931] sent a copy of the manuscript to Conrad Schlumbarger for criticism. The latter's comments were complimentary and the paper stimulated him and his associates to undertake a solution in terms of Bessel functions [*Stefanesco, Schlumberger*, and *Schlumberger*, 1930]. These two methods of solution were published over 25 years ago and both are still used in attempts to obtain numerical evaluations which can be used for practical interpretations. In each method, the calculations are involved and tedious. In the method of images, an infinite series must be summed; in the Bessel function method, an integral with an infinite limit must be evaluated. For the two-layer Earth, reasonably satisfactory tables and curves are at hand. Some curves are available for the three-layer Earth. However, only a few curves have been available for more than three layers, and this set is intended to meet the need and fill the gap. The evaluations were made possible by the availability of a modern high-speed digital automatic computer, financed by research grants, and by a cooperative effort of many persons, guided by the authors.

The theorist will be interested only to the extent of learning the methods of numerical evaluations. The practical interpreter will be intrigued by the album of curves, which can be used without reference to the text. Besides two short auxiliary tables, the text contains over 2400 tables of potential values, each for fourteen values of the argument. The album contains a sheet with twenty two-layer curves, 35 sheets with about 350 three-layer curves, and over 200 sheets with over 2000 four-layer curves. Each sheet of curves, except that for the two-layer Earth, represents one set of resistivity ratios. Each curve is labeled with the depths to the successive boundaries, assumed horizontal, the deepest always being six. Each curve has as ordinate the ratio of the apparent resistivity to the resistivity of the upper layer, and as abscissa the separation of the Wenner configuration, used in determining the apparent resistivity. As the Lee partitioning configuration is the same as the Wenner configuration except that the potentials are referred to the midpoint, the curves may be used equally well for either system. Each sheet is labeled with a four-digit code corresponding to that of the appropriate table of the text. In this code, the first digit represents the depth combination, in an arbitrary code of ten members, and the last three digits represent the lower three resistivities referred to the resistivity of the top layer, in an arbitrary scale of seven members. The interpreter does not need to know the code.

The use of the curves is direct. The apparent resistivity, as measured, is plotted as ordinate, and the separation is plotted as abscissa, on double logarithmic paper of five-inch cycles. An attempt is made to match the observed curve with a curve in the album. If a match is possible, the vertical index of the reference curve superposes on a depth of six units on the observed curve and the horizontal index of the reference curve superposes on the value for the resistivity of the upper layer on the observed curve. The label of the sheet and the curve furnish the ratios needed to determine the various depths and resistivities.

If no match is possible, the interpreter may conclude that the assumed conditions have not been met with sufficient agreement, or that the observed curve lies between two curves of the album. In the latter case, interpolation may be possible. However, as there are five parameters, no logical ordering of curves is possible and interpolation may call for copying on a single sheet curves from separate sheets of the album, often not close together. Also, it may be necessary to use interpolation in more than one parameter or of order higher than linear. In such instances, interpolation can be troublesome.

Experience can speed the recognition of curve types and the selection of album curves for matching. However, no rules can be given for the process, and with so many sheets, the selection can be tedious. For frequent use, microfilming of the plates may be advisable, so that frames can be inspected rapidly. After a preliminary selection, the actual album and observed curves should be used for matching. Personal judgment will play an important part in the selection and matching process and there will seldom be a unique match.

The text is adequate, but condensed. Occasionally a few words of explanation would clarify the text, as for example on page 21, where a reference to page 18 would clarify the choice of 1.6. A typographical error occurs on page 23, in the omission of the factor two in the second term of equation 29. In Figure 6, the resistivity ratios are not shown, although they are clearly indicated in the text. On page 7, the statement that Table C can be used for "any arrangement of electrodes" can be misleading, as the necessary values of the argument will seldom all occur in the tabulated list. Interpolation may be required and may lead to erroneous values. Some indication of the maximum possible and of the probable errors would have been valuable, but it is understandable that such estimates could not always be made. As smoothing was necessary, there is room for question as to the accuracy of the tables and auxiliary calculations, but it may be assumed that the authors have satisfied themselves that the errors lie within their accepted standards.

The curves leave something to be desired. Some printing is almost illegible. Many curves are poorly drawn, showing erratic humps, sharp changes in slope, inverted curvatures and failure to merge into asymptotes. One test curve calculated from the tables of the text did not accurately track the corresponding curve of the album. Although the curves may be sufficiently reliable for experimental measurements, departures

from ideal curves can complicate interpretations and even prevent adequate matching. However, until more precise tables are available, the present text and album will meet a need. Only the test of experience can determine whether the accuracy is sufficient, or whether the additional time and expense of greater accuracy and larger ranges of parameters would have been justified. If practical application proves satisfactory, the judgment of the authors will have been vindicated; if not, the present attempt and results can serve as a justification for further developments. (While this review was in press a supplement has been issued to show the degree of smoothing involved in the tables and curves. Also a few typical errors have been listed.—Ed.)

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STEFANESCO, S., C. SCHLUMBERGER, AND M. SCHLUMBERGER, Sur la distribution électrique potentielle autour d'une prise de terre ponctuelle dans un terrain à couches horizontales homogènes et isotropes, *J. Phys. Radium*, **1**, 132–141, 1930.

IRWIN ROMAN

SCHUCHERT, CHARLES, Atlas of Paleogeographic Maps of North America, John Wiley & Sons, 1956, ($4.75).

This Atlas represents the work of a lifetime of one of the world's foremost stratigraphers. Charles Schuchert started to compile the maps in 1904 or 1905 and was still plotting data in 1942, the time of his death. By 1910 he presented a series of 49 maps in his *Paleography of North America*, but realized that this was simply a pioneering effort. He believed that with careful correlation at least 100 time divisions could be represented by maps, and perhaps 125. But in his mind the maps were never finished, and so, at the time of his death remained unprepared for publication.

The best of Schuchert's maps have been selected by his secretary, Clara M. LeVene, and Carl O. Dunbar and have been arranged for publication. A new base map of North America was prepared and adapted from the latest Geologic Map of North America. John Sanders transferred the data to the new base, and Mildred P. Cloud prepared an index and cared for the editorial work involved in the legends. Altogether 84 maps are published in the Atlas on 8½ × 11 inch pages. They have reproduced nicely and appear in clearly legible form.

The areal extent of outcrop of the stratigraphic units represented are shown on each map, and then the interpreted extent of the seas. The page facing each map shows the stratigraphic interval represented and also the formations or stratigraphic units arranged by states, provinces, or regions like Labrador, Greenland, Mexico and Alaska. This feature makes the maps usable by anyone interested in paleogeography and paleotectonics, because as correlations are changed the maps can be changed. Also, the maps are of such size that new information can be added. An index of formations noted by Schuchert refers one to the map on which the unit is charted.

Facies are represented in limited form. Most maps simply portray marine seaways. Some show areas of non-marine deposition such as occurred in the Pennsylvanian, Permian, and Triassic, and two Permian maps show evaporite areas. Other times of evaporite sedimentation are not indicated. The Uppermost Jurassic map shows some of the batholithic intrusions of the Nevadan orogenic belt. Some of the Permian and Triassic maps indicate regions where volcanism occurred.

The maps must not be judged on the basis of stratigraphic information as of 1956. A vast amount of subsurface data have accumulated since Schuchert's last entries in 1942, and these new data have been very well analyzed in isopach, lithofacies, and paleotectonic maps by modern stratigraphers. Schuchert's maps do not pretend to do this. I like to think that Schuchert would have been in the forefront of present stratigraphic studies if he had been in his vigorous prime today and not 30 or 40 years ago. The Atlas is worth its publication simply as a document of the history of the science of geology. It is also basically significant to anyone wishing to persue paleogeography, and the maps will serve as a good starting point for interpretive studies.

I note that names of all land areas and seaways as used by Schuchert have not been included. Perhaps Schuchert only applied these names to his text book maps; perhaps they were deleted purposely so as to make the maps as documentary as possible.

A. J. EARDLEY

WAHLSTROM, ERNEST E., Petrographic Mineralogy, John Wiley & Sons, v + 408 pp., 1955, $7.75.

This text was prepared to fill the gaps between the original literature and the text-book presentations of the methods of microscopic-petrographic research, the identification of minerals, and (the ultimate goal of petrography) the classification of rocks. Of the eleven chapters in the book, the first three take up rather briefly (in 43 pages) the methods of petrographic research. These include the collection and preparation of samples, various methods of separating crushed rocks into fractions of the component minerals, chemical and microchemical tests, and a very concise review of optical crystallography. The brief treatment is offset by 25 pertinent references. Chapter 4 is devoted to the Universal Stage. The presentation is practical, well illustrated, and should prove very useful to students. Graphical Presentation of Data, and Common Petrographic Calculations, covering about 12 separate items, are tersely presented in 21 pages and constitute Chapter 5.

The core of the book consists of Chapters 6, 7, and 8 (193 pp.), which present in descriptive and tabular form the optical and physical data for the identification of minerals in thin sections and as crushed fragments. This will be the most useful and valuable part of the book. This reviewer feels that more use could have been made in these chapters of the methods of petrographic research as outlined in the first three chapters.

The last three chapters of the book (108 pp.) describe the composition, physical properties, and classification of igneous, sedimentary, and metamorphic rocks.

The abundance of well-drawn figures adds much to the readability and usefulness of the text. This book should prove a valuable laboratory companion for those who use the polarizing microscope.

GEORGE T. FAUST

HEINRICH, E. WM., Microscopic petrography, McGraw-Hill Book Co., 296 + xiii pp., 1956 ($6.50).

This book is designed to serve as an introduction to the study of rocks with the petrographic microscope. It assumes a knowledge of optical mineralogy and familiarity with the common rock forming and accessory minerals. It is suitable for classes at the initial to intermediate levels.

A short preliminary chapter (14 pages) entitled Methods of Microscopic Study outlines the preparation, staining and micrometric analysis of thin sections, the immersion method, examination with the binocular microscope, and special methods for study of aggregates containing both opaque and non-opaque minerals. Universal stage techniques are not mentioned although its use is now common enough so that introduction at the intermediate level is entirely feasible.

For each main class of rocks (igneous, sedimentary, and metamorphic) there is an introductory chapter on general principles. These chapters discuss theories of origin, classification, composition, properties and special features.

Following each of these chapters a descriptive one treats the respective class of rocks in detail. For each individual rock the treatment is systematic,—description, mineralogy, textures and microstructures, occurrence (and origin, where separate treatment is called for).

There are numerous well-chosen photomicrographs and drawings from thin sections. The quality of the paper is such that these are clearly reproduced and show the features plainly that they are intended to illustrate.

The book is admirably suited as a text-book in courses in petrography and elementary petrology and should find wide acceptance for this purpose.

EARL INGERSON

HAMILTON, WARREN B., Geology of the Huntington Lake Area, Fresno County, California; Div. Mines, Calif. Dept. Nat. Res., Special report 46, 25 pp., 1956, $0.75.

This report presents a detailed petrologic and geologic study of an area of about 160 sq. mi. The rocks are chiefly granitic in composition. The typical rock can be considered a quartz monzonite made up of about 20 pct quartz, 30 pct potash feldspar, 40 pct sodic andesine, 4 pct hornblende, and 6 pct biotite. The theories of origin are treated in detail.

GEORGE T. FAUST

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Notes and Personalia

Notes

CORRIGENDA—On page 489 of the June 1955 issue of the *Transactions* in the Letters to the Editor relating to Corrections to a Solution Concerning Hydrologic Frequency Analysis by J. T. de Oliveira, Eq. (26) is incomplete in that the right-hand term as shown should be multiplied by the factor $1/x$. The author notes his indebtedness to E. J. Gumbel for this correction.

On page 71 of the February 1956 issue of the *Transactions* in the paper by William Mansfield Adams two dots should be placed over φ in the first term of Eq. (1), each dot indicating differentiation with respect to time. The author also notes that on Figure 5 the values on the abscissa should be divided by a factor of two.

RECENT DEVELOPMENTS IN IGY—Various phases of the work of the International Geophysical Year, both the United States part and the part of other nations, are actively getting under way looking forward to the official opening date, July 1, 1957. The various expeditions to Antarctica are either on the ground or en route during this Antarctic summer, and the American bases are in operation. The one at the South Pole is under the direction of Chief Scientist Paul A. Siple. Albert Crary, Assistant Chief Scientist of the Expedition, is director of the scientific work at Little America V, Finn Ronne at the Ellsworth Station on the Weddell Sea Coast, and Carl R. Eklund at the Wilkes Station on the Knox coast. James A. Shear has been appointed scientific station leader for the Adare Station at Cape Hallett, which is a station operated jointly with New Zealand. George Toney has been named the Byrd Station scientific leader. Laurence M. Gould, Director of the U. S. IGY Antarctic Program and Chairman of the IGY Antarctic Committee; Harry Wexler, Chief Scientist of the U. S. IGY Expedition; and Gordon D. Cartwright of the U. S. Weather Bureau, who will be attached to the base of the USSR during the IGY period, have recently arrived in the Antarctic in connection with their duties.

In connection with the meteorological work, Wexler noted that the Antarctic is the only place in the world where ice deposits of the areal extent and thickness reminiscent of the great North American ice shield 20,000 years ago exist, and that, in addition to making measurements of solar radiation, ocean temperatures and currents, air temperatures and winds, the depth and temperature of the ice will be recorded. Deep holes will be bored in the ice to obtain cores which can be interpreted to give a record of past temperatures and precipitation amounts as far back as 10,000 years, using analyses of radio isotopes of oxygen and carbon. Flights made by U. S. aircraft from McMurdo Sound have revealed three extensive snow-free areas within 350 miles of the Pole. At least two of the bare areas, Plunket Point at the junction between Mill and Beardmore Glaciers and at the northwest side of Mill Glacier, are believed to afford airfield sites.

The Australians report that their aircraft from the Mawson Base have found an uncharted shelf gulf 100 miles long near Amundsen Bay in Enderby Land and a gigantic new glacier about 300 miles wide and 150 miles long moving down from the Antarctic mountains to Prydz Bay.

The main parties of the British IGY station at Halley Bay led by Robin Smart and for the Trans-Antarctic Expedition led by V. E. Fuchs left London in November, 1956, on the Danish ship *Magga Dan*.

Scientists of the USSR report that during the course of reconnaissance trips on the Antarctic Continent in the region of the Soviet Mirny Station (66° 34′ south, 92° 55′ east) an oasis was observed 350 km from Mirny which has been titled Bunger's Oasis. This is not covered with ice, and the various lakes are only slightly saline. It seems to have a microclimate of its own, particularly with regard to temperature and humidity. Preliminary investigations reveal that phenomena which bear on the IGY in meteorology and glaciology and perhaps also in biology make it desirable to establish a supplementary scientific station at this location (66° 16′ south, 100° 44′ east) which will be under the direction of the Polar Scientist Tcellichev.

The Belgians expect to establish their station about a year hence in the neighborhood of Breid Bay between 22° and 23° east to operate during the calendar year 1958 under the leadership of Gaston de Gelache, who is the son of the chief of the Belgian expedition which in 1898 was the first to spend the winter in the Antarctic.

The French Antarctic Expedition to Terre Adelie is under the leadership of Robert Guillard. There are two bases, one at Dumont d'Urville and the other at Scharcot. At the first location indicated, the lowest temperature observed thus far was −22.2° C with a maximum of 5° above. Wind had reached a velocity of 65 km per second.

The Argentine expedition to the Antarctic has established a new base on Thule Island in the Sandwich Islands group for exploration in the Weddell Sea area.

Work on the development of the satellite and its rocket vehicle has been progressing well, and in early December the U. S. National Committee for IGY met to review the work on this and the general budget for the U. S. work in connection with the IGY. The satellite is being constructed under the direction of the Office of Naval Research as Project Vanguard. It is anticipated that the satellite will receive a coat of pure gold 1/30,000 inch thick instead of the thin silver plate earlier contemplated. The vehicle launching the satellite will be a three-stage rocket to be fired from the Air Force Missile Test Center at Patrick Air Force Base in Florida. Project Director John P. Hagen has noted that much of the work relating to this has now moved to that location. The extensive plans for tracking the satellite are likewise progressing along with the satellite-orbit computation programs. Two computing and analysis centers are being established, one at the Naval Research Laboratory in Washington and the other at the Smithsonian Astrophysical Observatory in Cambridge. The first will handle the radio tracking system and the second will relate to the optical and visual observational programs. Because of the rapid speed of the satellite around the Earth in about 90 minutes, its tracking (including its timing) is of the utmost importance in connection with the scientific results anticipated under this program.

Plans for the work in the Arctic are likewise developing rapidly. Joseph O. Fletcher has been assigned to

duties in the formation of this program which will include the establishment of floating stations and a study of the ice conditions in the Arctic. Already, as a matter of routine, we are getting much information with regard to the Arctic, and so detailed plans such as those worked out for the Antarctic are not necessary.

The Executive Committee of CSAGI (the International Committee for the IGY) met in Paris on December 5 and 6, 1956, the International Committee relating to Oceanography met in Gothenburg, Sweden, in mid-January, 1957, and a conference on nuclear radiation was held in Utrecht, The Netherlands, January 22–26, 1957.

Much additional work, perhaps less spectacular and less large in scale, will be going on in various parts of the world. The Bolivian National Committee, for example, notes that in Bolivia investigations concerning the deeper structural characteristics of the Earth's crust in the Bolivian Andes will be investigated with the aid of the Carnegie Institution of Washington, using seismic waves generated by explosions.

Various manuals are in preparation for use in the IGY work, and it has been announced by the International office in Brussels that the ones on seismology, longitude and latitude, geomagnetism (volume 1), and on Antarctic radio communications are available in a temporary edition. Three volumes of the ionosphere manual were about complete, and geomagnetism (volume 2) on aurora and air glow is in the final stage of preparation.

The final calendar on regular world days (RWD) and world meteorological intervals (WMI) for the International Geophysical Year have been adopted on an international basis. The first world day will be July 4, 1957, with the first world meteorological interval bracketing the days from September 18 to 27, inclusive. A complete calendar may be secured by interested persons from the office of the U. S. National Committee for the IGY, 2101 Constitution Avenue, N.W., Washngton 25, D. C.

It was noted in the December, 1956 issue of the *Transactions*, page 797, that there is still need for scientific personnel for certain phases of IGY work and that these persons were hired separately by numerous organizations involved in the IGY work. Since then, a clearing house for these positions has been set up by the U. S. National Committee for the IGY. Interested persons should write to that committee at 2101 Constitution Avenue, N.W., Washington 25, D. C.

NINTH PACIFIC SCIENCE CONGRESS—The Ninth Pacific Science Congress will be held in Bangkok, Thailand, November 18–December 9, 1957, under the sponsorship of the Government of Thailand and the Science Society of Thailand. Persons from the United States interested in this Congress should write to the Pacific Science Board, National Research Council, 2101 Constitution Ave., Washington 25, D. C.

STUDY OF PHYSICAL-SCIENCE TEACHING IN SECONDARY SCHOOLS—The National Science Foundation announces a grant of somewhat more than $300,000 to the Massachusetts Institute of Technology to support a two-year study of physical-science teaching in secondary schools. This will cover the need for better textbooks, better materials, and better teaching techniques. The committee working on this matter will include some of the foremost physical scientists in the United States, many of them connected with other institutions.

SUMMER INSTITUTES FOR HIGH-SCHOOL AND COLLEGE TEACHERS OF SCIENCE AND MATHEMATICS—Approximately 4500 high-school and college teachers of science and mathematics will benefit during the summer of 1957 from teacher-training programs sponsored by the National Science Foundation at summer institutes in 95 colleges and universities throughout the country. Grants totaling $4,800,000 have been made by the National Science Foundation in support of this endeavor. Details of the program and the institutes at which courses will be given may be obtained from the National Science Foundation, Washington 25, D. C.

GRANTS TO AID HIGH-SCHOOL SCIENCE TEACHING—Grants totaling over $4,000,000 have been made by the National Science Foundation to 16 colleges and universities to support institutes designed to help high-school science teachers improve their knowledge of science subject matter. The schools include Harvard University, Ohio State University, Oklahoma Agricultural and Mechanical College, Oregon State College, Pennsylvania State University, Stanford University, Washington University, University of Chicago, University of Colorado, University of Illinois, University of Michigan, University of North Carolina, University of Texas, University of Utah, University of Virginia, and University of Wisconsin.

SYMPOSIUM ON SIZE AND SHAPE OF THE EARTH—A Symposium on the Size and Shape of the Earth, sponsored by the Institute of Geodesy, Photogrammetry and Cartography and the Mapping and Charting Research Laboratory of Ohio State University was held November 13–15, 1956, with the support of the National Science Foundation and the Graduate School of Ohio State University. Some 30 odd papers were presented by various authorities in the field.

NEW ADDITION TO GEOPHYSICAL LABORATORY OF MAGNOLIA PETROLEUM CO.—The Magnolia Petroleum Co. now has under construction a 10,000 square-foot, single-story administration building in connection with the company's Geophysical Laboratory on Harry Hines Boulevard in Dallas. The new facilities will relieve the crowded conditions in the present building and will provide space for library, conference room, classroom, drafting room, auditorium, dark room, and administrative offices, as well as for the creation of an acoustical well-logging service department.

INTERNATIONAL CONFERENCE ON SCIENTIFIC INFORMATION—The National Science Foundation, the National Academy of Sciences, and the American Documentation Institute have announced joint sponsorship of an International Conference on Scientific Information to provide for a thorough discussion of developments and research pertaining to the organization and dissemination of scientific information, with special emphasis on storage and retrospective search. It is anticipated that the Conference will be held in Washington, D. C., in November, 1958.

GROUND-WATER RECHARGE EXPERIMENTS NEAR AMARILLO, TEXAS—The U. S. Geological Survey has announced that, according to recharge experiments made in the Ogallala formation underlying the one square-mile section of land in the city of Amarillo's McDonald well field, over 10,000 acre feet of water can be stored. Wells of this field may be recharged at rates in excess of 1000 gallons per minute for a year or more without appreciably changing the water level in the ground-water reservoir beyond the limits of the well field. The report entitled "Artificial recharge experiments at McDonald well field, Amarillo, Texas" is to be published, but pending this copies of the report may be consulted at the offices of the U. S. Geological Survey in Washington, D. C., and Austin, Texas, and at the City Hall in Amarillo.

NEW WATER-SUPPLY PAPER ON GROUND WATER IN THAILAND—A new water-supply paper entitled "Reconnaissance of the geology and ground water of the Khorat Plateau, Thailand" is soon to be released by the U. S. Geological Survey. The Khorat Pleateau comprises some 155,000 square kilometers (60,000 square miles) underlain by gently inward dipping beds of sandstone and shale. Pending publication, a typewritten draft may be consulted in the offices of the Survey in Washington, D. C., and at the University of Alabama.

SECOND ANNUAL HURRICANE EVALUATION SYMPOSIUM—The Second Annual Hurricane Evaluation Symposium, sponsored jointly by Florida State University and the U. S. Weather Bureau, was held at the headquarters of the National Hurricane Research Project, West Palm Beach, Florida, on November 28–30, 1956. The principal speaker at a dinner meeting held on the evening of November 29 was Gordon Dunn. The first meeting of this series was held in November of 1955 at Florida State University in Tallahassee under the joint sponsorship of Florida State University and the U. S. Weather Bureau.

NEW SCRIPPS EXPEDITION—A new expedition of the Scripps Institution of Oceanography to the Revillagigedo Islands is now under way, with emphasis on geological and bathymetric exploration although other investigations will also be undertaken. These Islands, which include the site of Barcena Volcano, have been visited several times in recent years. Adrian F. Richards is the scientific leader of the expedition, which will include nine scientists, five of whom are from Mexico. The expedition is receiving the support of the Office of Naval Research.

NEW SUB-MINIATURE GYRO COMPASS—A new north-seeking gyro compass of battleship accuracy has been developed by the American Bosch Arma Corporation for the Engineer Research and Development Laboratories under the Corps of Engineers and has been tested in a mount near the pilot in a helicopter. It is small enough to be carried in one hand and is rugged enough to perform accurately in a tank operating in rough terrain.

MEETINGS OF THE WORLD METEOROLOGICAL ORGANIZATION—The Second Meeting of the WMO Commission for Maritime Meteorology met October 16–November 1, 1956, in Hamburg, Germany. Representing the United States as delegates were Newton A. Lieurance, Willard F. McDonald, and Paul Drouilhet. The United States team of observers included Alver E. Sik and J. J. Shule.

The WMO Commission for Climatology met in Washington, D. C., during January 14–22, 1957, with the U. S. Weather Bureau acting as hosts.

WEATHER RADAR EQUIPMENT PROGRAM—In connection with its program of expanding its weather radar equipment, the U. S. Weather Bureau has recently placed a contract in the amount of $3,800,000 to the Ratheon Manufacturing Company of Waltham, Mass.

INCREASE IN WATER USE IN THE UNITED STATES—Hydrologists of the U. S. Geological Survey, in a report recently released, show that there has been a 34 per cent increase in water use in the United States since 1950. This amounts to an increase of 440,000 million gallons per day. About 1,740,000 million gallons was withdrawn from the ground, lakes, and streams on the average each day of 1955. The uses included not only consumptive use and use for domestic and industrial supplies but also that used for the generation of water power. The water used for water power amounted to 1,500,000 million gallons per day—by far the largest use of water. Water used by industry largely for cooling and washing purposes is second in its total, with irrigation a close third, and the balance, 19,500 million gallons per day, was used for domestic, rural, and livestock purposes.

UNESCO STUDY OF THE HUMID TROPICS—Plans were laid at a UNESCO meeting at Kandy, Ceylon, in March, 1956 for tropical research in the humid areas of the world. It was pointed out that many million square miles of the Earth are in the humid tropics in which the temperature in the coldest month does not fall below 64° Fahrenheit and the rainfall is at least 27.5 inches. Some of these areas are almost uninhabited, while others are the most densely populated in the world. In 12 million square miles of the hot and humid parts of the Americas, Africa, Australia, and New Guinea the population is less than ten persons per square mile, but in the Ganges Valley it is about 1200 people per square mile; and in others, such as Bengal Delta and certain districts of Java, it is nearly 4000 per square mile. In these densely populated areas living standards are low, and heavy rains wash the fertility from the soil. Because of rapid bacterial decay, little humus is formed and there is a high prevalence of bacterial and insect-borne diseases. A permanent Advisory Committee on Humid Tropics Research was formed, and an invitation was received for the new Committee to meet in early 1957 at the Institute for Tropical Study and Research at Abidjan on the Ivory Coast in French West Africa. Another meeting on climate, vegetation, and land utilization in the humid tropics is scheduled to be held in connection with the Ninth Pacific Science Congress in Bangkok in 1958. Nineteen recommendations were laid before the Kandy meeting calling, among other things, for the classification of tropical soils, the role of organic matter and nitrogen compounds in these soils, and a system of fellowships

for research workers. The Kandy meeting recognized rice culture as a most valuable tropical vegetation because of the high food value of rice and the fact that the flooded fields do not allow the nutrient elements of the soil to be washed away.

FEDERAL EXPENDITURE FOR SCIENTIFIC RESEARCH AND DEVELOPMENT—A report of the National Science Foundation shows that $2.4 billion were spent in the fiscal year 1956 by the Federal Government for research and development. This represented a seven per cent increase over 1955. It anticipates that the total will reach $2.7 billion in 1956. It is noted that 25 agencies of the executive branch administer research and development funds, with about 99 per cent of the funds handled by eight agencies, namely, Department of Defense, Atomic Energy Commission, Department of Health, Education, and Welfare, Department of Agriculture, National Advisory Committee for Aeronautics, Department of the Interior, Department of Commerce, and National Science Foundation. The greater part of the funds are devoted to applied research and development, with basic research accounting for only about nine per cent of the total. About 47 per cent of the total was for research performed by the Government in its own laboratories, 38 per cent by commercial research organizations, 13 per cent through educational institutions, and the remainder through other groups. The physical sciences accounted for a total of 87 per cent of the funds, life sciences 11 per cent, and social sciences 2 per cent. Copies of the report entitled "Federal Funds for Science, V" may be secured for 35 cents from the Superintendent of Documents, Washington 25, D. C.

NEW ASTRONOMICAL OBSERVATORY AT THE UNIVERSITY OF WISCONSIN—Plans have been received and approved for the establishment of an astronomical research observatory to be located on a 53-acre tract 15 miles west of Madison, Wisconsin, as a part of the University of Wisconsin. The funds for the observatory have been made available through a gift from the Wisconsin Alumni Research Foundation. The equipment will include a 36-inch reflecting instrument to be installed in the late summer of 1957.

CORRECTION CONCERNING INSTITUTE OF RESEARCH FOR THE NEGEV IN ISRAEL—The news item on page 660 of the October, 1956 issue of the *Transactions* gave the impression that this institute is now actively at work. David H. K. Amiran, Director of the Research Council of Israel, has written to advise that the institute is still under construction in the city of Beer Sheeba and it is hoped that the first building will be opened within a few months. Up to now no research has been conducted. The title of the institute is "The Negev Research Institute," and its purpose is to serve scientists in research on arid zone problems, especially the Negev area, and will include both pure and applied research in biology, hydrology, soil science, climatology, physiology, chemistry, and other subjects as need requires. Work on the desalinification of water and the possibilities of irrigation with slightly saline water will be investigated.

NINTH GENERAL CONFERENCE OF UNESCO—The Ninth General Conference of UNESCO was held in New Delhi, India, opening on November 5. The new budget for the two-year interval 1957–58, estimated at $21,600,000, roughly a million dollars more than the budget from the previous biennium, was approved. Dr. Athelstan Spilhaus, Dean of the Institute of Technology at the University of Minnesota, was re-elected a member of the board for a four-year term by the largest number of votes received by any candidate. The meeting was held in a new hall built by the Government of India especially for this meeting. Tunisia and Morocco were elected to membership in UNESCO, bringing its total membership to 79 nations.

NEW SECTION OF SUN-EARTH RELATIONSHIPS AT THE NATIONAL BUREAU OF STANDARDS—A new Section of Sun-Earth Relationships at the Boulder Laboratories of the Bureau has been organized. Alan H. Shapley has been named as the head of the Section.

SPRING MEETING OF USA NATIONAL COMMITTEE OF URSI—The spring meeting of the USA National Committee of URSI (International Scientific Radio Union) will be held May 22–25, 1957, at the Willard Hotel in Washington, D. C. All of the seven Commissions will hold meetings. Details may be secured by writing to the Secretary of the USA National Committee, John P. Hagen, Naval Research Laboratory, Washington 25, D. C.

Personalia

GEORGE N. BRANCATO has been appointed Meteorologist in Charge of the Weather Bureau Office in St. Louis.

GORDON CARTWRIGHT, Chief of the Station Facilities and Meteorological Observations Section of the U. S. Weather Bureau, departed from the United States in December, 1956, for Cape Town, South Africa, where he joined the Antarctic Expedition of the USSR. He will represent the United States at the Soviet Antarctic Station at Mirny. Representing the USSR at the U. S. Antarctic Weather Central at Little America will be Vladimir Ivanovitch Rastorguev.

WALTER M. ELSASSER, formerly Professor of Theoretical Physics at the University of Utah, has joined the staff of Scripps Institution of Oceanography as Research Physicist.

FRANCOIS N. FRENKIEL, Principal Staff Member of the Applied Physics Laboratory of Johns Hopkins University has been appointed Consultant to the Applied Mathematics Laboratory of the David Taylor Model Basin in fluid dynamics research and related fields. His part-time association with the Applied Physics Laboratory includes his editorship on a new

series of monographs on applied mathematics and mechanics.

JOSEPH L. GILLSON of the E. I. du Pont de Nemours Co. has recently been given the D. C. Jackling Award of the American Institute of Mining, Metallurgical, and Petroleum Engineers.

LAURENCE M. GOULD, President of Carleton College, has been appointed Director of the United States IGY Antarctic Program and has left for the Antarctic. As Director of the U. S. program in the Antarctic, he will have the responsibility of the scientific program of geophysical observations planned for the Antarctic which calls for a network of six observation stations: Little America Station, Byrd Station, Pole Station, Weddell Station, Knox Station, and Adare Station, the last being a joint station with New Zealand.

WILLIAM C. HAYES has taken up duties as Economic Geologist with Missouri Division of Geological Survey and Water Resources, with headquarters at Rolla, Missouri.

HANS T. HESSELBERG, Director of the Norwegian Meteorological Institute for 40 years has recently received the annual prize of the World Meteorological Organization.

GEORGE C. KENNEDY of the Institute of Geophysics, University of California, Los Angeles, has been named the recipient of the 1956 Award of the Mineralogical Society of America. This Award is made annually to a scientist under the age of 36 for the most outstanding contribution to the mineralogical profession during the year.

H. B. KINNISON, who has served as District Engineer of the U. S. Geological Survey of the Surface Water Branch in Boston for the past 30 years, has been named Branch Area Chief for the Western States with headquarters in Menlo Park, California.

CHARLES E. KNOX, who has served as Assistant District Engineer of the U. S. Water Surface Branch in Boston for the past several years, has been named District Engineer to succeed H. B. Kinnison recently transferred to California.

FINLEY B. LAVERTY, Chief Hydraulic Engineer of the Los Angeles County Flood Control District, has recently been elected a Director of the American Society of Civil Engineers.

GARALD G. PARKER, Principal Geologist and formerly Chief of the Manpower and Training Section of the Ground Water Branch of the U. S. Geological Survey, has been put in charge of the new office of the General Hydrology Branch of the U. S. Geological Survey at Upper Darby, Pennsylvania. Other staff members in the Upper Darby office include Walter B. Keighton, Jr., Chemist, formerly of the Quality of Water Branch in Philadelphia; Allen G. Hely, until recently Engineer-in-Charge of the Surface Water Branch in Flagstaff, Arizona; and Franklin H. Olmsted, Geologist, formerly of the Sacramento office of the Ground Water Branch. The function of the new office in Upper Darby is to make a comprehensive study of the Delaware River basin.

MORTON RUBIN of the U. S. Weather Bureau has been appointed to serve as head of the International Weather Central being established at Little America V in Antarctica for the duration of the International Geophysical Year. He will be assisted by William B. Moreland, also of the U. S. Weather Bureau.

S. KEITH RUNCORN, Director of the Physics Department at King's College, Newcastle, England, made a series of lectures at the University of Texas on theories of the Earth's present and past magnetic behavior.

HAROLD J. SMITH has been designated as Meteorologist in Charge of the Weather Bureau Airport Station at Nashville, Tennessee.

JAMES S. SWEET of the U. S. Weather Bureau has assumed new duties as Consultant Hydraulic Engineer with the U. S. Operations Mission in Colombia.

DAVID K. TODD, Assistant Professor of Civil Engineering at the University of California, Berkeley, has been awarded a postdoctoral fellowship by the National Science Foundation for hydrologic studies in Europe during the calendar year 1957.

JOHN VON NEUMANN, member of the Atomic Energy Commission, was recently given the Award for Extraordinary Scientific Accomplishment by the American Meteorological Society "for his farsighted contribution to the science of meteorology and the national interests in developing the modern, high-speed electronic computer with meteorological application as an ultimate aim, and for his support and encouragement in organizing the world's first research group in numerical weather prediction."

HARRY WEXLER, Director of Meteorological Research of the U. S. Weather Bureau, left Washington, D. C., December 26, 1956 for Antarctica in connection with his duties as Chief Scientist for the Antarctic Program of the United States National Committee for the International Geophysical Year. He plans to return to the United States in April, 1957. He was recently given the Exceptional Service Award by the Air Force which consists of a medal and formal citation and is the highest award given by the Air Force. Paul Humphrey of the U. S. Weather Bureau was scheduled to accompany Wexler on the USS *Curtiss* when it sailed from New Zealand for Antarctica. Humphrey will assist in the establishment of the United States meteorological observation program for the IGY in Antarctica.

EVERETTE LEE DE GOLYER died in Dallas, Texas, December 14, at the age of 70. He was born at Greensburg, Kansas, and took his baccalaureate degree from the University of Oklahoma in 1911. He received a number of honorary doctorates, including one from the Colorado School of Mines, one from Southern Methodist

University, and one from Trinity College. Before the completion of his collegiate work, he began service with the U. S. Geological Survey in 1906 and from 1909 to 1914 worked as a geologist with the Mexican Eagle Oil Company, establishing his own office as a consultant from 1914 to 1919. His success in the matter of oil production began in 1910 when he staked the location in Mexico for Petero No. 4 well, which came in for 100,000 barrels of oil potential daily and produced a total of 130,000,000 barrels. In 1919 he established the Amerada Petroleum Corporation which was phenomenally successful in the matter of oil production. He established Geophysical Research Corporation in 1930 and was one of the organizers of Geophysical Service Incorporated. In 1936, in cooperation with Duncan A. McNaughton, he organized De Golyer and McNaughton, a consulting firm in Dallas. During the war years he served as Assistant Deputy Petroleum Administrator for War, Head of the Mission to Mexico Petroleum Administration for War, Head of the Interior Department's Petroleum Reserves Corporation Mission to the Middle East, and in various other capacities. He was the recipient of many honors and awards, among these the John Fritz Medal and the Anthony F. Lucas Medal. He had been a member of AGU since 1931.

NATHAN CLIFFORD GROVER, former Chief of the Water Resources Branch of the U. S. Geological Survey, died November 29, 1956 at the age of 88. He was born in Bethel, Maine, and took his baccalaureate degree at the University of Maine in 1890 and another at Massachusetts Institute of Technology in 1896. He was awarded an honorary doctorate at the University of Maine in 1930. He began his professorial career teaching at the University of Maine where he continued until 1903. From 1903 to 1907 he worked with the U. S. Geological Survey and from 1907 to 1911 with the J. G. White Company. He returned to the U. S. Geological Survey where he continued until his retirement. He officially retired in 1939, but during the war years he returned to active work with the Geological Survey to make his great fund of knowledge on water resources of the world available in our war effort. He became a member of the American Geophysical Union in 1930 and was President of the Section of Hydrology from 1939 to 1942.

HUGH CHESTER MITCHELL, astronomer and geodesist, retired from the U. S. Coast and Geodetic Survey, died November 20, 1956 at the age of 79. He was born in Jackson County, Texas, and took degrees at Notre Dame University in 1895 and 1898. In 1898 he entered the service of the U. S. Coast and Geodetic Survey where he continued in various positions until his retirement in 1945, excepting for the interval from 1912 to 1921, when he devoted his efforts to private affairs, chiefly in Texas. At the time of his retirement in 1945, he was principal mathematician for the Survey. He had been a member of AGU since 1930.

ERNST WANNER of the Swiss Meteorological Bureau died November 4, 1955 at the age of 55. He was born in Zurich, took his college work at the Technical Institute of Zurich and devoted most all of his professional life to the work and problems of meteorology in the Swiss Meteorological Bureau. He had become a specialist in the field of seismology and related aspects of geophysics. At the Rome meeting of the IUGG in 1954, he was elected Vice President of the Association of Seismology and the Physics of the Earth's Interior.

Union, Section, and Committee Activities

Proceedings of Executive Committee Meeting, American Geophysical Union November 17, 1956

The meeting was called to order at 13h 40m in the Board Room of the National Academy of Sciences—National Research Council Building, 2101 Constitution Avenue, Washington, D. C., by President Maurice Ewing.

Present—P. H. Abelson, L. H. Adams, L. T. Aldrich, Wallace W. Atwood, Jr., K. Hilding Beij, Lloyd V. Berkner, Walter H. Bucher, J. J. Capello, S. D. Cornell, Frank L. Culley, Maurice Ewing, Robert E. Gebhardt, Harry H. Hess, W. E. Hiatt, Albert J. Hoskinson, Benjamin F. Howell, Jr., Woodrow C. Jacobs, Henry R. Joesting, J. W. Joyce, Walter D. Lambert, Helmut E. Landsberg, Leonard M. Murphy, J. H. Nelson, James A. Peoples, Jr., Donald W. Pritchard, J. Frank Schairer, Waldo E. Smith, Henry Stommel, E. H. Vestine, Ralph N. Wilson, and George P. Woollard.

Approval of minutes—The minutes of the Executive Committee meetings on April 29 and May 2, 1956, published in the August 1956, issue of the *Transactions* (pp. 514–526), were approved.

General Secretary's Report

The last report of the General Secretary was that of April 29, 1956 published in the August issue of the *Transactions* (pp. 515–518). This report covers the interval subsequent to April 29.

On July 29 we suffered the loss by death of John Adam Fleming, our Honorary President. He served as General Secretary from 1925 to 1947. More than any other individual, he fostered and promoted the growth of the AGU and played a dominant role in setting the policies that have worked out so well through the years. In 1947 the office of Honorary President was created, and he was designated Honorary President for life. A biographical sketch appears in the opening pages of the October issue of the *Transactions*.

Publications—The following issues of the *Transactions* have been printed and distributed since our last meeting:

June 1956: 130 numbered pages and 18 unnumbered pages including 9¾ pages of paid advertising; edition of 6200

August 1956: 138 numbered pages and 22 unnumbered pages including 10¾ pages of paid advertising; edition of 6200

October 1956: 133 numbered pages and 19 unnumbered pages including 12¾ pages of paid advertising; edition of 6200

The Editorial and Publication Committee has held regular bimonthly meetings in this interval to consider its many problems, including the matter of how the present format of the *Transactions* may be further improved. There have been only favorable reactions received by the office with respect to the format inside, and while minor changes are contemplated, no substantial change is anticipated. The printer has advised that our printing costs will be increased about ten per cent beginning with the first issue of next year.

A new director of members will be published early in 1957.

Mrs. W. A. James of New Haven, Connecticut, has continued as our Advertising Representative and has steadily increased the volume of advertising. The October issue contains slightly over 12 pages; this is an increase of over 100 per cent from the six pages that we carried in August 1955. It is especially urged that any who have suggestions for advertisers, or who can be of definite aid in the securing of advertising, should advise or get in touch with Mrs. James.

Negotiations have been under way for some time for the reprinting of out-of-print numbers of our *Transactions*.

During the interval since the last meeting we have published Geophysical Monograph No. 1 entitled "Antarctica in the International Geophysical Year." In order to save time we published this ourselves, using our regular printer and the new format of the *Transactions*. This made it possible for us to complete the printing of the number early in September, less than two months from the time that the last paper was received. About 1400 copies of Monograph No. 1 were sold in advance of publication. The total sales now are roughly 1600. The total edition was 2500.

Considering the fact that members of the U. S. National Committee of IGY have expressed an interest in the monograph series as an outlet for at least some of the end product of the IGY effort, it would seem to behoove us to attempt to raise a monograph fund, say, of about $50,000 from foundations or other sources as a revolving fund for the publication of documents deemed to be worthy of publication in the monograph series. A revolving fund of $50,000 should permit publication of some 20 or 30 monographs without further financial worry. Suggestions are invited.

Vice President Berkner has suggested that immediately following the close of the IGY and perhaps for some years later there should be a series of carefully planned symposia relating to various facets of the IGY work, and that AGU as the other organization of the National Research Council relating to geophysics should contemplate taking an active role in these. AGU should appoint a committee to see what can be done to aid in this work.

Early this year it became evident that we should take steps to encourage the translation of Russian geophysical literature which is again becoming available in the Western World. To this end a letter was addressed to the National Science Foundation suggesting our willingness to help. Negotiations are now under way, and it is believed that a substantial grant will be forthcoming. At one time it was felt that we might attempt to build up our own staff of part-time trans-

lators, but the experience of others has been that this has not worked out very satisfactorily and that costs tend to run high and administration is difficult. Accordingly, we are now thinking chiefly in terms of a subcontractor already in the translating and publication business who can assure us that the translations are accurate and reflect the thought content of the originals. There was discussion as to whether we should translate complete journals, selected articles from various journals, the preparation and publication of extensive review articles, or simply the Russian abstracts. The thought at present is that one Russian journal, most likely *Izvestiia* (*Geophysics Series*) should be translated and published, and abstracts from various Russian abstract journals should be compiled, translated, and published. A third publication *Trudy* (*Geophysics Series*), which is more or less a monograph series, might be translated or not as indicated by a survey of the contents by competent readers of Russian. It is also thought that the first journal should be sold on a subscription basis, the funds from the sales to be added to the grant from the National Science Foundation. The abstract journal could be used in connection with surveys conducted by AGU to determine the needs and desires and the potential support of translation journals in this country. The third journal, *Trudy*, if a translation is undertaken, would be sold on a per-copy basis. The National Academy of Sciences has authorized AGU to accept grants totaling $60,000. The initial grant may be on the order of $40,000 to accomplish the tasks contemplated. It appears that the Foundation will require AGU to be indicated as the publisher of this material, and authorization of the Executive Committee will later be sought to authorize these publications if and as the plan for the grant materializes.

Appointment of new committees—President Ewing has been giving attention to the appointment of the Union's committees for the current triennium. Some of these committees have been appointed, namely, the Editorial and Publication Committee, the Committee on Audit, and the Committee on International Participation. By the time of the meeting on November 17 it is anticipated that other appointments will be approaching completion.

Membership—Membership data are:

Membership, April 25, 1956	5040	
Reactivated	5	
New members, April 26, 1956 to November 1, 1956, including some 40 applications now being processed toward membership	139	5184
Resigned	36	
Inactive	1	
Dropped (tentative)	172	
Deceased (reported since April 29, 1956)	20	229
Membership as of November 6, 1956		4955

A count was made of the members during the summer, the first actual count since about 1944. The number of members tabulated in the journal record is too low by 14 members. Accordingly, the new figure as of this date is 4969. These are broken down as follows: Regular paying members (members, associate members, and student members), 4884; life members, 78; ex officio members, 2; corresponding members, 5.

During the summer months, membership solicitation was at a low ebb, but spontaneous applications have come in to help maintain our membership. However, it is felt that with the enhanced interest in geophysics perhaps largely because of the work of the IGY, our regular membership might be increased by a thousand and our corporation membership by a hundred during the next year or so. To study what might be done during the summer months, an *ad hoc* Committee has appointed in July consisting of Helmut E. Landsberg (Chairman), Earl G. Droessler, Nathaniel C. Gerson, William E. Hiatt, Patrick M. Hurley, Joseph Kaplan, and Robert W. Olson to consider ways and means to increase the membership of the Union and to bring in a report at this meeting.

Two problems have come up with regard to membership. We now have a student grade of member which is not restricted with regard to nationality, and quite a number of non-Americans have come in under this provision. It is ordinarily anticipated that upon termination of student membership an individual will become an associate member. At the present time Article 2(d) of the Statutes indicates that non-citizens are not eligible for the associate grade. It is recommended that this provision should be changed so that at least those who are foreign student members are acceptable in the associate grade.

A second matter that has arisen relates to a trainee of the U. S. Coast and Geodetic Survey who is here from abroad and who has recently become a member. He has paid dues for two years but does not know how he can continue to pay dues when he returns home. There has never been any plan for the remission of dues of foreign members. Certain dangers are involved in this, but the matter should have the attention of the Executive Committee.

The following 20 deaths have been reported to the Union office since our last meeting: Benarthur C. Haynes, April 29, 1954; E. Russell Lloyd, February 14, 1955; Raymond C. Osburn, August 6, 1955; Greenleaf W. Pickard, January 8, 1956; W. Ayvazoglou, January 25, 1956; Carl A. Heiland, February, 1956; Jerry Nelson, February 20, 1956; Pedro C. Sanchez, March 17, 1956; M. A. Warren, April 30, 1956, Morris M. Slotnick, May 8, 1956; Walter S. Adams, May 11, 1956; John L. Rich, May 21, 1956; Samuel Jackson Barnett, May 22, 1956; William F. Foshag, May 22, 1956; Robin E. Spencer, June 3, 1956; George E. Merritt, July 5, 1956; John H. Gardiner, July 27, 1956; John A. Fleming, July 29, 1956; H. Kirk Stephenson, September 2, 1956; Norman Levi Bowen, September 11, 1956.

Dues unpaid—Owe for 1956	258
Partly paid 1956	18
Owe for 1955 and 1956	176
Partly paid 1955, 1956 unpaid	7

Finances—Below is a brief statement of our assets as of November 1, with comparison for the last two years.

	Nov. 1, 1956	Nov. 1, 1955	Nov. 1, 1954
Cash balance	$17,372[a]	$12,007	$8,742
Permanent Fund	14,075[b]	12,180[b]	10,657[b]
Emergency Fund	1,000	1,000	1,061
T. M. and E. Award Fund	1,251	985	215
	$33,698	$26,172	$20,675

[a] October issue of *Transactions* not yet paid; about $3400.

[b] Does not include accumulated interest on $2,368 of U. S. Savings Bonds.

The financial statement for the year ending June 30, 1956 has been completed and audited by the Audit Committee and will be presented later in this meeting.

Office staff and jobs—At the present time there are only three full-time staff members; a fourth, a stenographer-typist, is authorized. The office staff consists of James J. Capello, Ellen Lui, and Waldo E. Smith (the Executive Secretary). Glenda Quinn, who was a full-time staff member from the summer of 1954 to the fall of 1955 and continued on a part-time basis throughout the school year of 1955–1956 and on a full-time basis during part of the summer of 1956, is again on a part-time basis as Clerk-Stenographer. A high school boy who comes in after school each day serves as office boy and others are hired from time to time for packing the *Transactions* or other specific jobs.

Quarters—During the spring months, arrangements were completed to rent four rooms in the new building of the American Association for the Advancement of Science at 1515 Massachusetts Avenue, N. W. These quarters were occupied in late June, and a fifth room was rented the first of September. We now occupy slightly more than 900 square feet in Rooms 314 to 318, inclusive. The cost is $3728 per year instead of $3000 previously authorized. The increase was approved by a mail ballot of the Executive Committee.

The exhibit maps from 1939 have been turned over to George P. Woollard as authorized by the Executive Committee at its meeting last spring.

Air Force contract—The work on the Air Force contract was completed in July. This consisted of the editing of the papers of the Woods Hole Conference in September 1955, presumably for publication by the Air Force Cambridge Research Center as one of its report series. We have heard more recently that this has been turned over to Pergamon Press to be published as a commercial venture. We were hopeful at one time that we might publish this in our monograph series, but means seemed to be not available and so the project was dropped.

International matters—There was a meeting of the Committee on International Participation on the morning of November 17, and it is anticipated that the Chairman of this Committee will present a report subsequently. Here let it be noted that plans are developing for the Eleventh General Assembly of the International Union of Geodesy and Geophysics to be held in Toronto, Canada, September 3–14, 1957.

The International Association of Hydrology held a meeting in Dijon, France, September 20–26, 1956 on problems of ground water, glaciation, and the effect of reservoir storage. William E. Hiatt, Chief of the Hydrologic Services Division of the U. S. Weather Bureau, attended the meeting and was designated as Chief Delegate by the Section of Hydrology. Others attending from the United States included L. R. Beard, Ven Te Chow, Tate Dalrymple, Fred H. Klaer, Luna B. Leopold, M. I. Rorabaugh, and David K. Todd.

During the summer months the *Proceedings* of the International Association of Meteorology at the meeting in Rome were issued as a 500-page book by Butterworths at a price of 80 shillings. Thirty copies were sent without cost to addresses in the United States, chiefly to institutions concerned with meteorology, the list having been compiled by the officers of the Section of Meteorology.

There is a concerted effort to increase the subscription list of the *IUGG News Letter*, and although the subscription list in the United States is larger than that from any other country, we are aiding in this matter as best we can. A special announcement was inserted in the October issue of the *Transactions* calling attention not only to the *News Letter* but also to the *Bulletin Geodesique* and the *Proceedings* of the International Association of Meteorology above cited, and, when it was determined that a half page would be unused in the advertising section of this issue of the *Transactions*, we compiled an advertisement which appears therein.

Meetings—A meeting of the Pacific Northwest Regional Group will be held November 8–9, 1956 in Seattle. An interesting program is in hand including papers not only in Meteorology and Hydrology but also in Terrestrial Magnetism and Electricity and in Oceanography. Included in the program is a symposium on the ground-water aspects of the disposition of radioactive liquid wastes. This Committee was reorganized following the election of last February, and C. A. Barnes is now Chairman of the Regional Committee and Franklin I. Badgley is the Secretary-Treasurer.

The American Association for the Advancement of Science is meeting in the New York area between Christmas and New Year. As usual, they invited *AGU* as one of their affiliates to participate in the meeting, making any arrangements for special AGU sessions that seem desirable. No plans were developed to this end, but AGU is co-sponsor of a symposium on geochronology that is being arranged by J. L. Kulp of the Lamont Geological Observatory.

The Pacific Southwest Regional Group is planning to hold a meeting in Sacramento, California, February 14–15, 1957. The new officers include Vito A. Vanoni, Chairman and R. Corday Counts, Jr., Secretary.

Our Annual Meeting will be held April 29 to May 1, 1957, the week following the meeting of the National Academy of Sciences.

National Research Council report—The report of AGU to the National Research Council for the year ending June 30, 1956 was recently forwarded by the President to the NAS-NRC.

A Conference on the Practical Utilization of Recorded Knowledge was held in Cleveland at which we were invited to send a representative but rather only offered certain suggestions and a request that we be kept informed.

A Symposium on the Size and Shape of the Earth was held at Ohio State University, November 13–15, 1956, sponsored by the Institute of Geodesy, Photogrammetry, and Cartography and the Mapping and Charting Research Laboratory of that University.

AGU was invited to send a representative to the

commissioning of the Research Vessel *Crawford* on June 13, 1956 by the Woods Hole Oceanographic Institution.

Richard M. Field, Director of the American Institute of Geonomy and Natural Resources, held a meeting in the auditorium of the Cosmos Club on the evening of October 8 at which the John Fleming Medal for the Advancement of Human Welfare through Outstanding Accomplishments in Science was awarded for the first time. The posthumous award was made to Fleming. Walter D. Lambert made the citation, and the Medal was transmitted to his daughter Margaret through Field.

A. NELSON SAYRE, *General Secretary*

Action on the General Secretary's report—The report was accepted.

Reports of Standing Committees

Editorial and Publication—A. Nelson Sayre, chairman was absent because of illness. There was extensive discussion of the proposal to translate Russian journals and abstracts. Mention was made that some authors publish essentially the same paper in as many as five or six journals. There was also mention that certain translation projects are now under way in the United States, Canada, and Great Britain and that we should take care to avoid duplication. Our plan is to publish one complete journal at the present plus the Russian abstracts that relate to all phases of geophysics. A motion was passed authorizing the General Secretary to proceed with the publications along the lines indicated in his report, to be financed by funds received from a grant from the National Science Foundation.

There was discussion of the frequency of the publication of the directory of members but no decision was reached. The present interval is about two years. The thought was expressed that this might be issued triennially with a list of corrected addresses published every year but this was thought to be too cumbersome and perhaps almost as expensive as the issuance of a new directory each year. The directory has extensive use and the suggestion was made that we explore the possibilities of receiving aid from the National Science Foundation in order that this might be issued annually. With regard to those who have not paid dues for 1955–1956, it was agreed that though they cannot be dropped from membership at this time, that in sending dues notices to them for 1957, their attention should be called to the fact that a new directory will be issued early in 1957 and that unless their membership is brought up to date, their names will be omitted from the new directory.

With regard to the monograph, the thought was expressed that the margin of the receipts over expenditures for Monograph #1 might be set up as a special monograph fund. The thought was also expressed that we might earmark the interest on our permanent fund for purposes of publication. President Ewing requested Budget Committee to take these and other possibilities under consideration. It was suggested that various scientific publishing houses as well as the university presses might offer possibilities.

It was moved by Vice President Berkner, and approved, that the Executive Committee go on record as congratulating the Executive Secretary on the quality and speed with which Geophysical Monograph #1 was published.

It was reported that Miss Marjorie Hooker is working on the index for the *Transactions* 1945–1955 and expects to have this done in February. The index will presumably then be available by about next June.

International Participation—J. W. Joyce, Chairman, mentioned that the Committee held a meeting on the morning of November 17. The Committee dealt with future problems of the IUGG and details of the kind of organization and structure it should have. The Eleventh General Assembly is to be held in Toronto, September, 1957. The number of delegates, and means of drawing up a list were also discussed. Joyce noted that it was tentatively agreed, subject to general acceptance of this idea by the IUGG and our Canadian hosts that there be eight delegates to the Union as a whole, three delegates to each Association, plus, *ex officio*, the U. S. officers of the International Union and its Associations, a total of slightly over thirty. These would have specific administrative functions with respect to IUGG. Other scientists and technologists would be designated as accredited participants.

A motion was made by Beij that because the NRC must get into touch with the Department of State at an early date in this regard, the President of AGU and the Chairman of the Committee on International Participation be authorized to prepare a list of delegates in accordance with the procedure proposed by the Committee on International Participation, and also that the Executive Committee instructed the President that the President shall be chief delegate of the U. S. delegation and that the Chairman of the Committee on International Participation should be one of the delegates. This motion was passed contingent upon the general acceptance of the idea of limited delegations and that delegates should be those who have official administrative functions to perform at the General Assembly. Other geophysical scientists and technologists from the United States and other countries would as accredited participants. Family members and others would attend as guests. The Canadian National Committee has reserved some 1800 rooms for this assembly.

W. W. Atwood, Jr., noted that the current ceiling on U. S. contributions and dues to ICSU is $9,000, established in 1935. This is very unrealistic in the current day and the State Department is now seeking a ceiling of $90,000.

W. E. Hiatt reported briefly on the meeting of the International Association of Hydrology held at Dijon, France, September 20–26, 1956, which he attended as chief delegate of our Section of Hydrology.

Nominations—L. H. Adams has been appointed as Chairman for the current triennium.

Statutes and By-Laws—K. Hilding Beij has been named Chairman for the current triennium.

It was noted that at the meeting last spring the decision was made to change the name of the Section of Terrestrial Magnetism and Electricity to Section of Aeronomy and Geomagnetism to agree with that of the International Association. This has yet to be placed before the membership for ballot and before the Council of the National Academy for approval. It is awaiting the placing of other items on a ballot.

It was recommended and approved that the last paragraph of By-Law 20 relative to discounts accorded to members on purchases of publications of the Union be modified to read: "Each person and organization in

good standing in any class of membership may purchase any available publication of the Union at a discount from printed price-list to non-members. The General Secretary is authorized to establish discounts for sales of publications." As this appears in a by-law it does not require approval of the membership but only publication of the intent to change, with a thirty-day waiting period following publication and with subsequent confirmation within a year by the Executive Committee.

Attention was called to the fact that according to the first paragraph of By-Law 20, members of AGU have until July 1 to pay their annual dues before they are considered delinquent. In the past this has been interpreted to mean that they shall receive their publication for the first half of the year. It was moved and approved that dues notices should be sent out as early in December as possible with the indication that those who have not paid by February 15, 1957, would be removed from the mailing list for the *Transactions*, and that this be referred to the Committee on Statutes and By-Laws in order to formalize this procedure.

Article 3(d) of the Statutes defining Associates, indicates that these must be citizens of the United States of America. There is no such qualification for student members and inasmuch as it is expected that these will become associate members upon termination of their student status, Article 3(d) should be modified appropriately. It was approved that the words "and nationals of other countries" be inserted in Article 3(d) after the words "Citizens of the United States of America" and that this matter be referred to the Committee on Statutes and By-Laws for any other rectification necessary in the wording, in order that this may be placed promptly before the membership for ballot.

It was moved and approved that our statutes should be so changed that the Vice President should automatically become President in the case of the death of the President. The matter was referred to the Committee on Statutes and By-Laws for proper wording.

Budget—It was noted that Earl G. Droessler has been appointed Chairman of the Committee for the current triennium.

Meetings—P. H. Abelson has been designated as Chairman of the Committee for the current triennium. He asked for suggestions for the Annual Meeting, particularly in the nature of symposia and noted that he had suggestions for symposia on glaciology and on tracer elements in geophysics. Atwood suggested that some time might be devoted to the role of AGU in IUGG, a little more than comes out in a business meeting. Bucher suggested that whatever is done must be on specific topics, and suggested a symposium on satellites. Others suggested symposia on the magnetic fields of the Earth and on the ice age.

Berkner suggested that we develop a regular fall meeting away from Washington at one of the universities to bring AGU to the membership in various parts of the country. It was noted that under our regional plan we have a meeting in the Pacific Northwest for November and in California in January or February. Meetings should be held in more diverse locations geographically speaking and receive stronger sponsorship from the office of AGU.

Membership—W. E. Hiatt had no report.

The report of the *ad hoc* Committee on the membership problem was presented and discussed (see Appendix 1). D. W. Pritchard noted that he felt that increasing our membership by a thousand we should take pains to avoid lowering the standards. He notes that the Section of Oceanography represents a group of professional oceanographers. On one of the new lists he mentioned that one man proposed for full membership is a newspaper man and raised a question concerning accepting other than professional scientists in the full membership grade. It was pointed out that section affiliation, once a person is a member, can be changed at the request of the member. It was also mentioned that other groups such as the American Meteorological Society attempt to discriminate between professional members and others and frequently find themselves in difficulty. The President expressed the thought that this question should be given study by the Membership Committee.

Other aspects of the *ad hoc* Committee's report, under the chairmanship of Helmut Landsberg, involved the idea that three committees be established, one on corporation membership, one on regular membership, and one on student membership and that each of these groups should be approached separately. With regard to student membership, it was pointed out that thus far we have none transferring from the student grade to the associate membership grade but that the office had looked upon this as being an automatic step when a student member ceases to be a student. It was moved and approved that the *ad hoc* Committee's report be accepted.

The application for corporation membership by the Ralph M. Parsons Company was approved.

Audit—A. G. McNish has been designated Chairman for the current triennium. The report of the Committee was presented and accepted (see Appendix 2).

Reports of Special Committees

Geophysical and Geological Study of Continents—George P. Woollard has been appointed Chairman but the Committee has not yet been organized. He hopes to have this Committee promulgate more work among universities.

Cosmic-Terrestrial Relationships—E. H. Vestine has been designated as the new Chairman and welcomes suggestions as to whether the Committee should go on doing what has mainly been a reporting job or whether it should go ahead and do pioneer work. It was pointed out that in the first instance the Committee was appointed as one to engage in pioneering work.

Award of William Bowie Medal—Chairman still awaiting designation.

Resolutions—John N. Adkins has been designated as Committee Chairman.

Award in Terrestrial Magnetism and Electricity—W. B. Agocs has been appointed Chairman.

Tellers—J. H. Nelson has been appointed Chairman.

Advertising—There has been no such committee at the present but the President has felt that such a committee might help to increase the revenue from advertising in the *Transactions* and in the directory. Companies who are furnishing the extensive instrumentation for the IGY should be urged to advertise. The President indicated that he would appoint an *ad hoc* Committee and will appreciate suggestions on how to make it effective. It has been mentioned that the name of our publication tends to be against it in

the solicitation of advertising. It was agreed that this should be left to our Committee on Advertising for study and recommendation.

Relations of AGU with AGI—The President noted that this committee is yet to be appointed. H. R. Joesting, one of AGU's two representatives on the AGI Board presented a report by E. A. Eckhardt, the other representative (see Appendix 3). After extensive discussions, it was agreed that a carefully worded questionnaire should be sent to our members, and that in view of the benefit many of our members received through receipt of *Geotimes*, AGU should make a token contribution of $50 to AGI for the current year. It is felt that the situation within AGI is changing and that the outlook is broadening rapidly to embrace much more of the geophysical than was hitherto the case.

Relation of AGU to IGY—Noting that the IGY group is essentially an *ad hoc* group, the thought has been expressed from time to time that AGU should be prepared to take over certain functions in relation to IGY as the U. S. National Committee for IGY winds up its activity after the close of the Geophysical Year in 1958 and that even now plans should be laid bearing on the end product of the IGY endeavor in order that proper conferences and publications may be developed. It is planned that the President will appoint a committee to see in what ways AGU can serve best in this matter.

Reports of Sections

Volcanology, Geochemistry, and Petrology—President J. Frank Schairer noted that at a meeting of the Executive Committee of the International Association of Volcanology in Paris last spring, a proposal was made to change the name of the Association and to broaden the Association's scope. He noted proudly that we have already taken this step.

National Academy of Sciences—National Research Council

Earth Sciences—Chairman H. H. Hess asked for suggestions as to what the Division of Earth Sciences might do to continue the work of the Committee on Geologic Time.

Physical Sciences—Our representative, Walter H. Bucher, noted that he had attended a meeting of that Division and that a major part of the day was devoted to two subjects, namely, a tendency towards fragmentation in science, and the needs of education in science in the matter of public relations. S. D. Cornell reported that since last spring the Academy has appointed an Advisory Board of Education on which are representatives of the eight Divisions of the Council. This group is charged with drawing together the total interests of the Academy Council and with the problems of education in science. It would be glad to receive the views and expressions from AGU.

Affiliated Organizations

American Geological Institute—In addition to the matters discussed above, it was mentioned that Walter H. Bucher has been designated to succeed E. A. Eckhardt who has served as one of our representatives through two terms. Henry R. Joesting continues as our other representative. Paul L. Lyons has been appointed representative on AGI's Government Relations Committee.

Adjournment—The meeting adjourned at 17h 25m.

A. Nelson Sayre, General Secretary
Waldo E. Smith, Executive Secretary

Appendix 1—Report of Committee to Study AGU Membership Committee Organization

H. E. Landsberg, Chairman

Earl Droessler — Patrick M. Hurley
Nathaniel C. Gerson — Joseph Kaplan
William E. Hiatt — Robert W. Olson

History—Late in July 1956, the Vice President of the Union, Lloyd V. Berkner acting for the President, appointed the undersigned as an *ad hoc* committee to study the organization of the AGU membership committee. The business of the *ad hoc* Committee was primarily conducted by mail, although several of the Washington members met twice for informal discussions. We also had the benefit of advice from J. W. Joyce and the Executive Secretary.

Task—The terms of reference of the *ad hoc* Committee stated its task as follows: To examine into the question of how best our Membership Committee might be organized to secure, without lowering standards, at least 1000 new members, 100 corporation members, and a continuing feed of student members who should form the major eventual source of membership.

Specific Discussion

The three different classes of membership: regular, corporation, and student seem to require separate approaches. To each group different aspects of AGU activities appeal.

Regular members—A large reservoir of potential members are the big organizations. Many of them are at present government groups. (Among them are the U. S. Coast and Geodetic Survey; the U. S. Geological Survey; the U. S. Weather Bureau; the Air Weather Service; the Hydrographic Office; the Geophysics Research Directorate; Central Radio Propagation Laboratory; Snow, Ice, and Permafrost Research Establishment; Naval Research Laboratory; National Advisory Committee for Aeronautics.) It has to be brought home to the members of these organizations, as well as to employees of some of the larger geophysical companies that membership in the AGU carries with it professional advantages, such as prestige and easy access to technical advances through the *Transactions*. Senior staff members of these organizations are most likely to be able to impress their colleagues with these facts.

Corporation members—There are a number of reasons why corporations would want to join the AGU. These range from philanthropic motives to the competitive realities of the business world. Among the latter is the need to keep corporations' names before prospective employees in a tight technical labor market, before prospective customers for equipment and services, before groups who dispose of sizeable sums for contracts. Persons familiar with industrial and commercial contacts who know the procedures by which the companies

handle such affairs should participate in this phase of the membership campaign. It is likely that individuals with 'big names' in the field, whose accomplishments are well known should undertake the approach. The effort may have to be quite diffuse because of many major centers of industrial firms who might be potential corporation members. Among them are New York, Philadelphia, Chicago, Houston, Dallas, Tulsa, San Francisco, Los Angeles, Washington, and Boston.

Student members—The future of AGU is tied to the coming generation. They should join at an early stage of their careers, at least not later than their enrollment as senior or graduate students in geophysics. These young people can best be reached by their teachers. The advantages of membership 'from the ground floor up,' the mental stimulus of the *Transactions* and the feeling of belonging can be made obvious. This type of membership should be obtained with a minimum amount of red tape.

Specific Recommendations

It is recommended that:

(1) The Membership Committee of the AGU have three sections, one primarily responsible for obtaining regular members, the second for corporation membership, and the third for student membership.

(2) The chairman and vice chairman of these three sections under a general chairman form a steering group for the coordination of their respective drives and a pooling of campaign material.

(3) The section for regular membership have as members senior staff members from all major organizations employing large numbers of geophysicists.

(4) The section for corporation membership be appointed from among the senior men in the geophysical business and that it have subcommittees in the large business centers of the country where the firms' interests in geophysics are located.

(5) The section for student membership be composed of a professor from each of the schools having curricula in one or more of the geophysical disciplines.

(5a) These professors be individually empowered by the Executive Committee to accept for student membership any bonafide student of their institution upon payment of the proper dues, without further reference to the Executive Committee of the AGU.

General discussion—Our discussions and recommendations should be interpreted in the light that the high scientific standards of the AGU are to be maintained and that membership be primarily expanded to emphasize the research character of the Union. To this and other ends the membership committee and its sections will need suitable 'ammunition.'

For this purpose brochures outlining the advantages and privileges of membership should be prepared. Sample pages of the *Transactions* might be included. The international aspects, the IGY connections, and the interdisciplinary character of AGU are strong points of appeal. This as well as other aspects of a membership drive will fall on the Executive Secretary's office. For example, the members of the envisaged section on regular members will need up-to-date information on present membership from their respective organizations. They will then know whom to approach and from whom they can expect help. For the influence it may have on prospective corporation members a list of prominent AGU members who hold important executive positions in industry, universities, and government would be helpful. In this connection possible visits to various centers by the Executive Secretary with local members of the membership committee might be helpful. Also, members who speak in meetings and seminars on geophysical subjects might stress AGU's important role.

General Recommendations

It is recommended that (1) three brochures for membership drives be prepared, one for each class of prospective members; (2) special membership lists be prepared designed to aid in the drive; (3) a travel allowance be given the Executive Secretary so that he may assist local members in recruiting; and (4) a mail campaign be instituted by the Executive Secretary's office to reach prospective members in smaller organizations or out-of-way places.

For Consideration of Other Committees of the Union and the Executive Committee

The following thoughts are transmitted without specific recommendation because they exceed our terms of reference but have a strong bearing on a membership campaign.

Membership drives are usually only as successful as the inducements an organization has to offer. It is therefore quite clear that AGU's general policies will have to reflect obvious advantages.

(1) One of them is, of course, the *Transactions*. The technical contents should be the primary appeal. From comments received it leaves something to be desired in a few sections. One of the prime problems is prompt publication. (AGU is now in general publishing papers within six to eight months of the final receipt.—Ed.) Any organization which can do this will be favored by the scientists in this field. This requires prompt review and a prompt answer whether or not an article is acceptable. Thought should be given toward perhaps discriminating between members and non-members in publishing articles, with the former enjoying priority. With the IGY coming up there should be perhaps a special label for articles dealing with IGY results and particularly prompt publication. This would probably be of considerable appeal. For corporation members perhaps invitations to write from time to time short articles on the geophysical work and interests of the corporation, that is, an expanded 'professional card' might be of some interest.

(2) Meetings are another problem. The annual meeting in Washington is, of course, a fine traditional affair. However, for distant members thought should be given to more organized meetings in other parts of the country. At present this seems to be a catch-as-catch-can affair.

(3) A question which should also be raised: Should there be student chapters at various colleges and universities, with a regular meeting schedule?

(4) Also, how can the Union use its affiliation with the National Research Council and its position as U. S. Committee for the IUGG to the advantage of present and prospective members.

(5) There is undoubtedly greater interest than ever in geophysics because of the IGY. The Union should grasp all possible opportunities to help in the follow-through on research and evaluations subsequent to the end of IGY.

Appendix 2—Report of the Committee on Audit for the Fiscal Year Ending June 30, 1956

A. G. McNish, Chairman
E. B. Roberts R. H. Weightman

Your Committee on Audit has examined the books of the American Geophysical Union for the fiscal year ending June 30, 1956, and finds them in agreement with the statement of the Union's finances supplied by the Executive Secretary.

At the beginning of the current fiscal year the cash assets of the Union amounted to $17,075.33 consisting of $21,230.97 on deposit in the Riggs National Bank adjusted for $4,155.64 to cover checks outstanding. At the end of the current fiscal year the Union had a cash balance of $17,319.67 consisting of $20,177.29 on deposit in the Riggs National Bank adjusted for $2,857.62 to cover checks outstanding plus an auxiliary interest-drawing cash account of $9,500.00 with the Interstate Building Association. The Union also has Series F bonds in the amount of $2,368.00 (purchase price) and $10,707.07 on deposit in savings and building and loan associations making up the Permanent Fund. In addition, $1,000.00 is held in the Emergency Fund in the Prudential Building Association and $1,000.58 of the T. M. and E. Award Fund on deposit in the Liberty Building Association.

Your Committee has examined the evidence of these assets which support the report of the Executive Secretary. Our report is not based upon a completely detailed audit of all financial transactions of the Union but on a careful examination of certain essential aspects to give the Committee complete confidence in the soundness of this report.

Your Committee wishes to compliment the office of the Executive Secretary for the excellent state in which the accounts of the Union are kept, all details being subject to documentary verification.

Operating Statement

(Fiscal year ending June 30, 1956)

Receipts			
National Research Council grant			$400.00
Income			
Dues, 1953 and earlier	$228.00		
1954	367.50		
1955	4,102.50		
1956	31,764.12		
1957 et seq.	77.33		
Corporation Memberships	2,200.00		
Life Memberships	400.00	$39,139.45	
Sales of publications			
Transactions	$10,669.74		
Reprints	4,208.89		
Miscellaneous	35.50	14,914.13	54,053.58
Contributions to Permanent Fund			284.00[a]
Interest on Permanent Funds			364.83
Interest on T. M. and E. Award Fund			30.39
Air Force Contract			5,271.68[a]
Bibliography of Hydrology, 1951–1954, contract			1,971.07[a]
Advertising receipts			2,837.15
Sale of equipment (2 fans)			35.00[a]
Miscellaneous			156.94
Total receipts			$65,404.64
Disbursements			
Publishing *Transactions*			
Printing		$12,934.30	
Preparing copy		7,049.69	
Honoraria to editors		1,350.00	
Mailing		1,103.71	
Advertising expense		2,545.91	$24,983.61
Reprints			1,890.93
General expenditures (office of the Union)			
Salaries (including Federal Social Security)		$15,560.79	
Stationery and supplies		1,457.71	
Postage and communications		1,593.29	
Office equipment		127.11	18,738.90

Expenses, Section of Hydrology		4.77
Expenses, Section of Meteorology		5.74
Expenses, Committee on Membership		15.00
Expenses, Meetings		
Annual meeting	$997.70	
Regional meetings	88.57	1,086.27
National Academy of Sciences pension plan		962.62
Investment: Deposited with Prudential Building Association as part of Permanent Fund		630.00[a,b]
Air Force Contract		4,640.98[a]
Bibliography of Hydrology, 1951–1954, contract		1,964.60[a]
Bowie Medal		13.60
Interstate Building Association (original deposit on auxiliary account, cash reserve)		9,500.00[b]
Moving office		190.55
Miscellaneous		137.51
Total disbursements		$64,765.08

[a] Non-budget items.
[b] These are actually transfers of funds; the amounts remain available to AGU.

Excess of receipts over disbursements

Receipts	$65,404.64
Disbursements	64,765.08
	$639.56

Statement of assets and liabilities as of June 30, 1956 (See page 1116 of December 1955 *Transactions* for statement of assets and liabilities as of June 30, 1955)

Assets

Cash Reserve			
On deposit in Riggs National Bank, including former Robert E. Horton Fund of $1,180.91	$17,319.67[a]		
On deposit in Interstate Building Association	9,500.00	$26,819.67	
Permanent Fund			
Series F bonds purchased prior to July 1, 1948 (maturity value $3,200), at cost	$2,368.00		
On deposit in Northwestern Federal Savings and Loan Association as of July 1, 1956	9,928.36		
On deposit in Prudential Building Association as of July 1, 1956	778.71	13,075.07	
Emergency Fund			
On deposit in Prudential Building Association as of July 1, 1956		1,000.00	
T. M. and E. Award Fund			
On deposit with Liberty Building Association as of July 1, 1956		1,000.58	$41,895.32
Bills Receivable			
Dues			
1956 only	$4,671.00		
1955 and 1956	1,398.00	$6,069.00	
Publications			
Transactions (including subscriptions)	$609.69		
Reprints	366.64		
Miscellaneous	10.85	987.18	7,056.18
Miscellaneous			127.00
			$49,078.50

Liabilities		
Bills Payable and advance payments		
Dues in advance (1957 et seq.)	$123.03	
Subscriptions in advance (1957 et seq.)	20.00	
June 1956 *Transactions*	3,386.35	
Miscellaneous (mainly credits % overpayments)	35.51	$3,564.89
Surplus (Capital Account)		45,513.61
		$49,078.50
[a] Riggs National Bank statement of June 30, 1956		$20,177.29
Less checks outstanding		2,857.62
		$17,319.67

Appendix 3—Report of Representative of the American Geophysical Union on the Board of Directors of the American Geological Institute

The AGI Board met at Minneapolis on Friday, November 2, 1956. Both representatives of AGU on the AGI Board were present. A statement prepared at the request of the Geological Society of America outlines a financial program for AGI and has been approved by a substantial majority of its directors by letter ballot distributed last summer.

The member societies have responded well in assuming responsibility for the full financial support of the basic operations of AGI. At and since the meeting, five of them have announced increases in their contributions for a total of over $9000 annually. Since the total increase required from this source was somewhat less than $11,000, the balance should be forthcoming from action to be taken by the remaining eight member societies.

To the best of my knowledge, AGU is the only member society which does not make even a token contribution for the support of AGI. I recommend that a nominal contribution of $100 be made and that an insert be prepared to be included in some future mailing which goes to all AGU members. The insert should serve to obtain answers to the following questions:

(1) Do you have an interest in the American Geological Institute? (Yes) (No)

(2) Please check to which other member society of AGI you also belong. (List would be shown.)

The returned answers should very simply determine how many AGU members are interested in AGI who are not members of another member society. Both of your representatives feel strongly that the minimum contribution of AGU should be based on the magnitude of this number. The circulation of *GeoTimes* would presumably be limited to the individuals composing this group.

It is a well-known fact that the Earth-science professions are not successful in competing with other natural sciences, notably chemistry and physics, for the young people who are about to choose their careers. The supply of competent Earth scientists falls short of the national needs. The profession needs to do something about this and the AGI is likely to be the most effective agency for identifying the best point of attack and concentrating upon it. In providing a forum for the discussion of the basic problems which all Earth scientists have in common and a framework within which all who are interested can cooperate with others to achieve results for the common good, AGI can operate with an effectiveness and authority which derives from its being the recognized representative of substantially the entire profession.

E. A. Eckhardt

Union, Section, and Committee Activities

Pacific Northwest Meeting held in Seattle, November 8–9, 1956—A Pacific Northwest Regional meeting was held at the University of Washington in Seattle, November 8 and 9, 1956. The official registration was 60. A varying number of visitors also attended the individual sessions. Those in attendance came largely from Washington and Oregon with some from Idaho, British Columbia, Utah, California, and Chile. Thirteen papers were presented at the technological sessions treating subjects in hydrology, meteorology, oceanography, seismology, and terrestrial magnetism and electricity, thus falling within the scope of five of the eight sections of the Union.

A business meeting was held on November 8 at which time it was decided to hold the 1957 meeting in Portland, Oregon. A meeting of the regional committee members was held on November 9 and Norbert Leupold (P. O. Box 5082, Portland 13, Oregon) was selected as chairman-elect for the year beginning July 1, 1957, and also designated as overall chairman for the 1957 meeting.

Franklin I. Badgley
Secretary-Treasurer,
Pacific Northwest Regional Committee

(Please note the corrections from the December issue,

page 801, which indicate that Clifford A. Barnes of the University of Washington had been designated as Chairman. He continues as Chairman until July 1, 1957 following which the chairmanship will be taken over by Norbert Leupold of Portland, Oregon as indicated in the note above.)

The North Central Regional Committee has now organized and designated Edward M. Brooks, University of St. Louis, Chairman, and Russell G. Mann of the U. S. Weather Bureau River Forecast Center of St. Louis as Secretary-Treasurer.

Geophysical Society of Hawaii (Mid Pacific Regional Group of AGU) met in Honolulu December 31, 1956 to hear talks by Laurence M. Gould, President of Carleton College and Harry Wexler, Director of Meteorological Research for the U. S. Weather Bureau who stopped briefly in Honolulu on their way to Antarctica in connection with their work for IGY.

Special Announcements

THIRTY-EIGHTH ANNUAL MEETING, WASHINGTON, D. C., APRIL 29–MAY 1, 1957—We call last-minute attention to the previous announcements regarding this meeting that have been published in the *Transactions*, particularly that in October, 1956, page 663, relating especially to program matters, and that in the December, 1956, issue, page 802, bringing these matters up to date and giving information regarding block booking of hotel rooms.

Program details are rapidly being settled, and some Sections have their programs largely filled. The programs close officially on March 5, 1957, in most cases but, as noted in the December announcement, the closing date for certain portions was January 25. Three copies of the titles and abstracts should be in, at the latest, by March 5, 1957, with word concerning the amount of time desired (10 to 20 minutes normally allowed) and projection equipment needed. Filled programs will be closed in advance of March 5.

ELEVENTH GENERAL ASSEMBLY OF IUGG—Plans regarding the program and other details for the Eleventh General Assembly of IUGG to be held in Toronto, Canada, September 3–14, 1957, are rapidly developing. Those who desire to attend from the United States should get in touch with the office of AGU as promptly as possible.

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Transactions
American Geophysical Union

VOLUME 38 APRIL 1957 NUMBER 2

The Observation Accuracy of High-Range Geodetic-Type Worden Gravimeters

WILLIAM E. BONINI AND GEORGE P. WOOLLARD

Abstract—The operation of two high-range geodetic-type Worden gravimeters on a program to establish primary gravimeter stations around the world afforded an opportunity to obtain detailed information on the accuracy of this type of instrument. A comparison of the instruments is made as to: (1) gravity intervals over a range of five gals, and (2) the drift characteristics and loop closures. The relative accuracy of observation with these gravimeters is ±0.3 mgal; and, therefore, when calibrated on an absolute basis a similar accuracy of observed gravity should be possible.

Introduction—Woollard [1950] reported the first use of a high-range Worden gravimeter to make intercontinental gravity measurements of geodetic value. Since that time, high-range geodetic-type instruments have been used extensively by Woollard and by others. The difficulties of making long-distance measurements and of calibrating high-range instruments have been subjects of recent papers [*Woollard, Harding*, and *Rose*, 1955; *Woollard* and *Bonini*, 1955]. The use of two high-range geodetic-type Worden meters, W-147 and W-10F, in the 1954 World-Wide Gravity Program sponsored by the Office of Naval Research and the Air Force Cambridge Research Center, at the Woods Hole Oceanographic Institution afforded a unique opportunity to study in greater detail the accuracy of high-range gravimeter measurements. The coarse spring dial characteristics of both instruments was known from a previous study [*Woollard, Harding* and *Rose*, 1955, pp. 19–20]. The measurements were made at common locations over a range of five gals, and great effort was made to control drift and tare errors (sudden jumps in reading). Since modern pendulum values were available for check purposes over most of the range covered, and since the operational difficulties and errors as to site, drift, tares, and coarse spring dial irregularities were minimized, these measurements represent the most complete test of the observational accuracy of gravity measurements made to date using high-range Worden gravimeters.

Operational procedure—In order to minimize drift and tare errors Military Air Transport and commercial air services were utilized to establish gravimeter observations at a series of primary locations (black circles in Figure 1) between which multiple interval measurements were made. Between most of these primary stations the gravity intervals were determined three times (each line in Figure 1 represents one connection). The interval between Washington and Dhahran (Saudi Arabia) was measured three times; the ties between Dhahran and Manila, Manila and Tokyo, and Tokyo and San Francisco were measured twice each on turn-around flights (for example, Dhahran to Manila to Dhahran to Manila, etc.) and the Tripoli-Rome interval was observed four times (two turn-around flights). These stations were used as bases for the other measurements and as reference sites for comparative measurements at the Cambridge and Gulf-Wisconsin pendulum sites and at the fundamental gravity stations in 37 countries.

Using Rome as a base, closed loops were flown to (1) Madrid and Lisbon, (2) London, (3) Zurich and Belgrade, (4) Frankfort and Paris, and (5) Athens and Ankara. From London a loop was flown to Copenhagen and to Oslo, Bödö, and Tromsö in Norway. Using Tripoli as a base a circular loop was flown to Johannesburg and from there a short loop closure within South Africa to Durban and Capetown. From Manila, a closure was made to Darwin and Sydney, Australia, and from Sydney to New Zealand.

Comparison of instrumental drift—During the six months the survey was conducted (June-November, 1954) the instrumental drifts were reasonably constant at near 0.05 mgal per hour. Two factors caused the drift to vary: (1) agitation and (2) temperature effects.

Agitation was caused by travel on rough roads

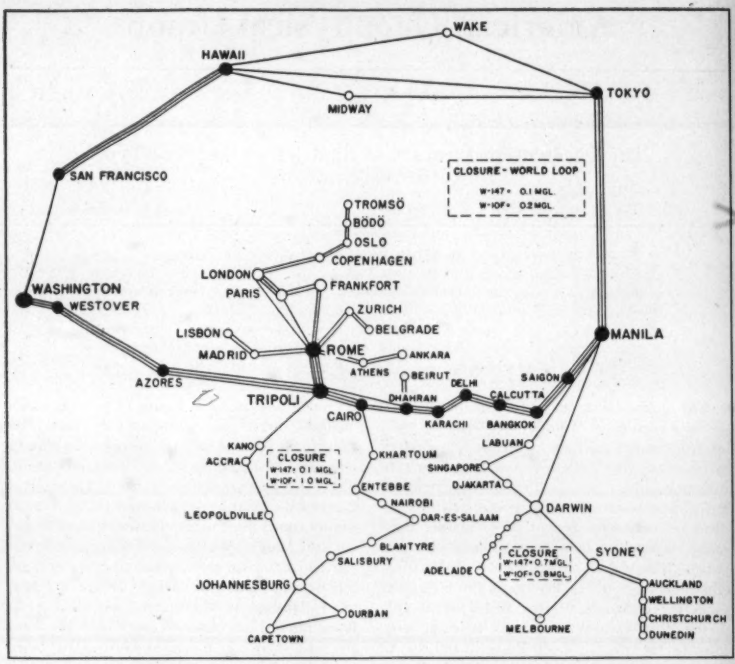

FIG. 1 – 1954 World-Wide Gravity Program, schematic plan of air flights to establish gravity intervals; each line indicates one air trip; black circles are designated primary stations

during surveys to tie local stations to the airports and produced an increase in rate of drift of both instruments. In Figure 2, the second, third, and fourth readings at Khartoum, taken in the process of a local survey by jeep, indicate a progressive increase in drift rate with time. In the case of both instruments, the average drift rate at Khartoum is greater than it otherwise might have been.

Because of the combination of imperfect temperature compensation and great changes in temperature, while moving from one climatic zone to another, temperature effects produced a change in the normal drift rate (Fig. 2 and 3). It is a matter of coincidence that one instrument was slightly undercompensated and the other over-compensated (perfect compensation being very difficult to obtain), thereby affecting the rates in opposite directions. Figure 2 illustrates the East African line and shows W-10F having an increasing drift rate when moved from a warm to a cold environment and vice versa, whereas W-147 acted in the reverse direction (but not as severely) decreasing drift from warm to cold and vice versa. At Cairo observations over a four-day period showed W-10F drifting negatively, changing to positive and returning to normal at Tripoli. There was no evidence to support the view that sudden jumps in scale reading are caused by rapid temperature changes, but rather they cause a change in drift lasting a period of days. Temperature changes in the New Zealand loop (Fig. 3) were less severe. Only W-10F was affected, and the drift changes were similar in direction for similar temperature changes in Africa.

The fact that agitation affected the drift rate of both instruments in the same direction and temperature effects in the reverse direction made it possible to separate these effects.

Closure errors—Table 1 indicates the errors of

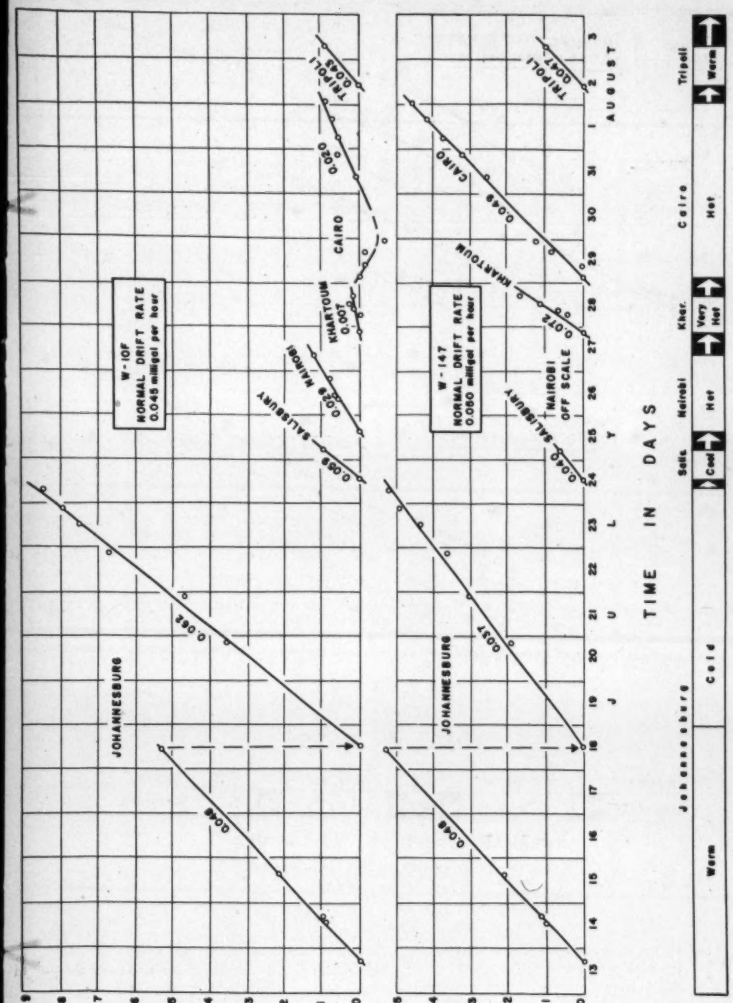

FIG. 2 – Drift comparison of W-147 and W-10F on an interrupted flight from Johannesburg to Tripoli (East African line) and temperature variations

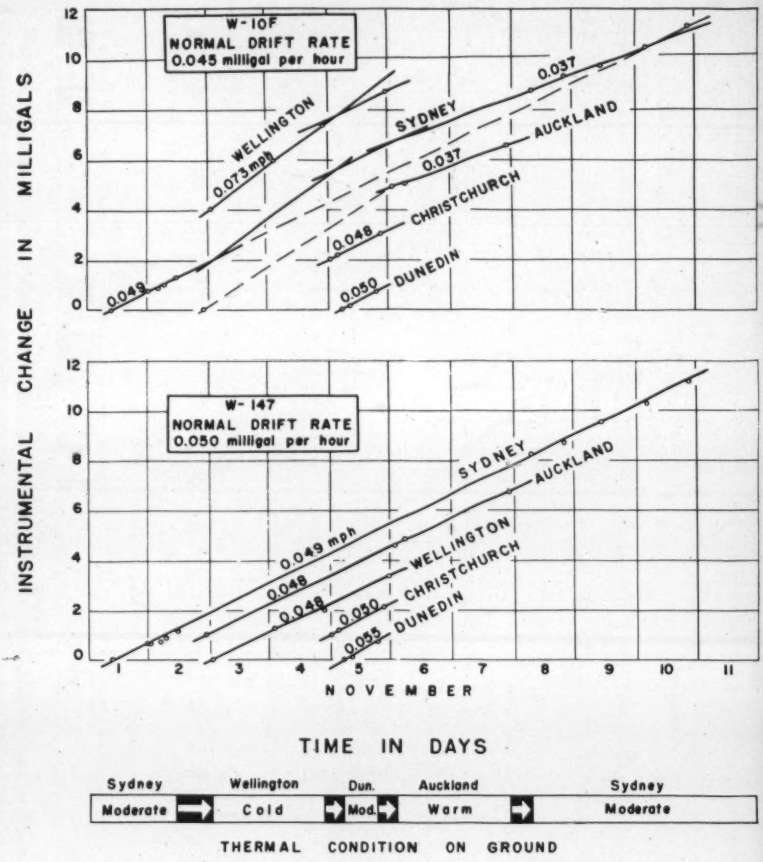

FIG. 3 – Drift comparison of W-147 and W-10F and temperature variations on a closed loop from Sydney to New Zealand

TABLE 1 – *Errors of closure of each instrument after correction for drift*

Survey	W-147	W-10F
	mgal	mgal
World-Wide loop	+0.1	−0.2
African loop	−0.1	−1.0
Australian loop	+0.7	−0.8

closure on the most important loops. The World-Wide loop is a composite made from the average of the several intervals between the primary stations, whereas in Africa and Australia there is one closure each.

The large closure error of W-10F in Africa was found to be a tare between Johannesburg and Blantyre by comparison with the gravity interval

TABLE 2 – *Comparisons of gravimeter values at Gulf pendulum sites*

Station	Pendulum value	Gravimeter values		Difference from pendulum values	
		W10f	147	W10f	147
	gal	gal	gal	mgal	mgal
North America					
College, Alaska	982.2455	982.2458	982.2461	+0.3	+0.6
Whitehorse, Y. T., Canada	981.7487	981.7488	981.7488	+0.1	+0.1
Fort St. John, B. C.	981.4054	981.4051	981.4052	−0.3	−0.2
Edmonton, Alb.	981.1681	981.1678	981.1678	−0.3	−0.3
Lethbridge, Alb.	980.7590	980.7570	980.7574	−2.0	−1.6
Ottawa, Ont.	980.6206	980.6210	980.6211	+0.4	+0.5
Cutbank, Mont., U. S. A.	980.6077	980.6084	980.6083	+0.7	+0.6
Great Falls, Mont.	980.5263	980.5269	980.5269	+0.6	+0.6
Huron, S. D.	980.4535	980.4533	980.4536	−0.2	+0.1
Billings, Mont.	980.3697	980.3704	980.3703	+0.7	+0.6
Madison, Wis.	980.3688	980.3689	980.3689	+0.1	+0.1
Sheridan, Wyo.	980.2254	980.2263	980.2265	+0.9	+1.1
Washington, D. C.	980.1007	980.1007	980.1007	0.0	0.0
San Francisco, Calif.	979.9863	979.9863	979.9864	0.0	+0.1
Casper, Wyo.	979.9550	979.9560	979.9557	+1.0	+0.7
Tulsa, Okla.	979.7665	979.7662	979.7662	−0.3	−0.3
Cheyenne, Wyo.	979.6990	979.7004	979.7000	+1.4	+1.0
Denver, Colo.	979.6103	979.6106	979.6104	+0.3	+0.1
Amarillo, Tex.	979.4243	979.4237	979.4233	−0.6	−1.0
Houston, Tex.	979.2983	979.2984	979.2984	+0.1	+0.1
San Antonio, Tex.	979.1966	979.1975	979.1974	+0.9	+0.8
Laredo, Tex.	979.0801	979.0806	979.0805	+0.5	+0.4
Monterrey, N. L., Mexico	978.8049	978.8056	978.8057	+0.7	+0.8
Tamazunchale, S. L. P.	978.6596	978.6592	978.6597	−0.4	+0.1
Chapulhuacan, H.	978.4842	978.4840	978.4844	−0.2	+0.2
Jacala, H.	978.3301	978.3221	978.3221	−8.0	−8.0
Ixmiquilpan, H.	978.1675	978.1677	978.1679	+0.2	+0.4
Tacubaya, D. F.	977.9419	977.9420	977.9417	+0.1	−0.2
El Zarco, D. F.	977.7676	977.7673	977.7672	−0.3	−0.4
Paso Cortez, D. F.	977.5709	977.5708	977.5709	−0.1	0.0
Europe					
Teddington, England	981.1968	981.1968	981.1967	0.0	−0.1
Oslo, Norway	981.9277	981.9275	981.9274	−0.2	−0.3
Copenhagen, Denmark	981.5582	981.5580	981.5577	−0.2	−0.5
Frankfurt, Germany	981.0613	981.0609	981.0608	−0.4	−0.5
Rome, Italy	980.3640	980.3638	980.3638	−0.2	−0.2
Africa					
Cairo, Egypt	980.2910	980.2910	980.2911	0.0	+0.1
Tripoli, Lybia	979.5873	979.5873	979.5874	0.0	+0.1
Khartoum, Sudan	978.3031	978.3032	978.3031	+0.1	0.0
Nairobi, Kenya[a]	977.5412	977.5397	977.5391	−1.5	−2.1
Johannesburg, South Africa[a]	978.5504	978.5490	978.5490	−1.4	−1.4
Capetown, South Africa[a]	979.6486	979.6469	979.6471	−1.7	−1.5
Pacific-Asia					
Honolulu, Hawaii	978.9526	978.9525	978.9529	−0.1	+0.3
Tokyo, Japan	979.8009	979.8015	979.8019	+0.6	+1.0
Clark Air Force Base, P. I.	978.3965	978.3965	978.3964	0.0	−0.1
Muntinlupa, P. I.	978.3620	978.3620	978.3621	0.0	+0.1
New Delhi, India	979.1362	979.1361	979.1362	−0.1	0.0

[a] The departure of about 1.5 mgals with both gravimeters from the pendulum values in South Africa is believed due to a tare in the pendulum results.

of W-147, which closed well. The large closures in the Australian area were found to be errors between Darwin and Adelaide, where landing fields were grass or gravel, suggesting that errors might be associated with the many rough landings.

Relative accuracy of gravimeter measurements— The calibration of both instruments was put on an absolute basis through the reoccupation of Gulf pendulum sites in North America, Europe, and Africa. Table 2 gives comparative results for both

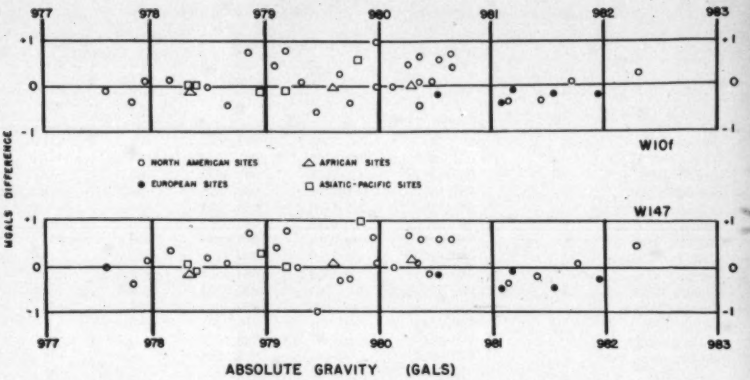

FIG. 4 – Difference in gravimeter values from preliminary Gulf pendulum values in North America, Europe, Africa, and Asiatic-Pacific area

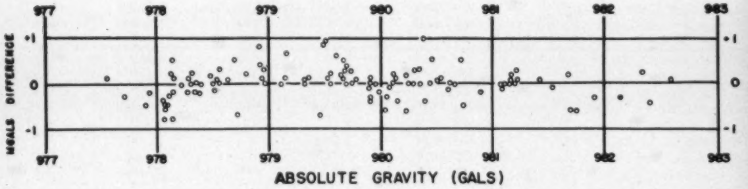

FIG. 5 – Variation in gravimeter values on global basis, W-147 relative to W-10F

gravimeters with these pendulum values. Figure 4 shows the comparisons graphically. Since the two instruments have quite different coarse-dial characteristics and temperature-adjustment effects, the degree of agreement in the results for each and the agreement with the pendulum results gives a good indication of the accuracy obtained. If the difference between the gravity values predicted by each gravimeter is statistically analyzed, the measurements are seen to agree on the average to ±0.4 mgal. The standard deviation, however, is only 0.3 mgal over the five-gal range covered. The maximum divergence was 1.0 mgal and that for only one station. The divergence in values is shown graphically in Figure 5. Comparative values at key sites are tabulated in Table 3. Practically all of these values are for airport sites taken at field level on the field side of the terminals.

The calibrations of both instruments appear to be linear, after allowing for the idiosyncrasies of the coarse spring dial systems [see *Woollard, Harding* and *Rose*, 1955]. Neglect of this factor would have given a much greater spread in the result.

Advantages of the two-instrument operation—The following are advantages of observations with more than one instrument at the same time: (1) It allows a comparison of gravity values of the different high-range instruments, where there is no question that both instruments were read at exactly the same place (a frequent difficulty). (2) The cause of drift irregularities can frequently be ascertained, and in many cases it eliminates question as to whether an irregularity is caused by changes in drift, or sudden jumps in scale reading. (3) Many times, when it is not possible to make turn-around measurements to control drift or tares, closure errors can be corrected at the proper places by comparison of intervals of both instruments (as long as both instruments have not sustained an identical tare). (4) The comparison of the accuracy of one instrument versus another is more precise, since there is a large number of common station occupa-

TABLE 3 – *Comparison of results, gravimeters W10f and W147*

Station	W10f	W147	Difference
	gal	gal	gal
Australia			
Adelaide Parafield Airport	979.7053	979.7056	+0.0003
Alice Springs New Airport	978.6541	978.6542	+0.0001
Brisbane Eagle Farm Airport	979.1602	979.1602	0.0000
Canberra Fairbairn Airport	979.6206	979.6212	+0.0006
Daly Waters	978.3892	978.3890	−0.0002
Darwin Airport	978.3154	978.3156	+0.0002
Kallista pendulum station	979.9102	979.9102	0.0000
Katherine	978.3449	978.3449	0.0000
Leigh Creek Airport	979.3205	979.3206	+0.0001
Melbourne Essenden Airport	979.9631	979.9632	+0.0001
Sydney, Kingford-Smith Airport	979.6995	979.6995	0.0000
Sydney Rose Bay Flying Boat Base	979.6967	979.6970	+0.0003
Tennant Creek Airport	978.5291	978.5291	0.0000
Azores			
Lages Terciera Island (Portuguese Civil) Terminal	980.1763	980.1764	+0.0001
Belgian Congo			
Leopoldville Airport	977.9515	977.9510	−0.0005
Denmark			
Copenhagen, Kastrup Airport	981.5575	981.5574	−0.0001
England			
Blackbushe RAF Base, London	981.1555	981.1555	0.0000
Bovingdon RAF Base	981.1935	981.1937	+0.0002
London Airport (old terminal)	981.2020	981.2020	0.0000
Grosvenor Naval Hdqs., London	981.2007	981.2008	+0.0001
Northolt Airport (Civil term.), London	981.2086	981.2087	+0.0001
Hendon RAF Base	981.2071	981.2074	+0.0003
National Physical Lab., Teddington	981.1966	981.1967	+0.0001
Egypt			
Cairo International Airport (Farouk Field)	979.3158	979.3158	0.0000
France			
Marseille, Marignane Airport	980.4878	980.4883	+0.0005
Paris, Orly Airport (MATS Terminal)	980.9164	980.9162	−0.0002
Germany			
Frankfurt, Rhein-Main Airport	981.0560	981.0560	0.0000
Frankfurt, Sindlingen Institute	981.0609	981.0608	−0.0001
Wiesbaden Air Force Base	981.0611	981.0611	0.0000
Gold Coast			
Accra Airport	978.1151	978.1148	−0.0003
Greece			
Athens, Hellinikon Airport	980.0592	980.0589	−0.0003
Hawaii			
Honolulu, Hickam Air Force Base	978.9332	978.9335	+0.0003
India			
Calcutta, Dum Dum Airport	978.8072	978.8074	+0.0002
New Delhi, Palam Airport	979.1338	979.1339	+0.0001
Indonesia			
Djakarta, Kemajoran Airport	978.1641	978.1639	−0.0002
Italy			
Rome, Ciampino Airport	980.3478	980.3478	0.0000
Japan			
Tokyo, International (Haneda) Airport	979.7737	979.7738	+0.0001
Lebanon			
Beirut, Bir Hassar Airport	979.6861	979.6866	+0.0005
International Airport	979.6919	979.6924	+0.0005
Lybia			
Tripoli, Idriscivil (Castel Benito) Airport	979.5376	979.5376	0.0000
Wheelus Air Force Base	979.5873	979.5874	+0.0001
Malaya			
Singapore, Kallang Airport	978.0818	978.0812	−0.0006

TABLE 3—*Continued*

Station	W10f	W147	Difference
	gal	gal	gal
Midway			
Sand Island, U. S. Naval Station	979.4984	979.4993	+0.0009
New Zealand			
Auckland, Whenuapai Airport	979.9410	979.9409	−0.0001
Christchurch, Harewood Airport	980.4967	980.4968	+0.0001
Dunedin, Taieri Airport	980.7372	980.7367	−0.0005
Wellington, Paraparaumu Airport	980.2100	980.2102	+0.0002
Nigeria			
Kano Airport	978.1355	978.1350	−0.0005
North Borneo			
Labuan Airport	978.0961	978.0956	−0.0005
Jesselton Airport	978.1280	978.1275	−0.0005
Sandakan Airport	978.0913	978.0909	−0.0004
Norway			
Bödö, Flyplass Airport	982.3876	982.3872	−0.0004
Oslo, Fornebu Airport	981.9312	981.9309	−0.0003
Trondheim, Vaernes Airport	982.1534	982.1531	−0.0003
Tromsö, Sea Plane Base	982.5716	982.5717	+0.0001
Nyasaland			
Blantyre, Chileka Airport	978.2167	978.2167	0.0000
Pakistan			
Karachi, Mauripur Airport	978.9579	978.9580	+0.0001
Philippine Islands			
Clark Air Force Base	978.3961	978.3961	0.0000
Manila, Muntinlupa Magnetic Obs.	978.3620	978.3621	+0.0001
Portugal			
Lisbon, Portela de Sacavem Airport	980.0794	980.0793	−0.0001
Inst. Geof. e Cadastral Pendulum Rm.	980.0900	980.0896	−0.0004
Porto, Observatorio Metereologico	980.2800	980.2800	0.0000
Sarawak			
Kuching Airport	978.0763	978.0756	−0.0007
Sibu Airport	978.0790	978.0783	−0.0007
Saudi Arabia			
Dhahran Air Force Base	978.9987	978.9987	0.0000
South Africa			
Capetown, Wingfield Airport	979.6490	979.6491	+0.0001
Durban National Airport	979.3673	979.3674	+0.0001
East London Colondale Airport	979.5459	979.5461	+0.0002
Johannesburg, Jan Smuts Airport	978.5497	978.5497	0.0000
Kimberley Airport	978.8875	978.8879	+0.0004
Port Elizabeth Airport	979.6510	979.6512	+0.0002
Pretoria, Zwartkop Airport	978.5986	978.5989	+0.0003
Southern Rhodesia			
Salisbury, Belvedere Airport	978.1479	978.1481	+0.0002
Spain			
Getafe Air Force Base	979.9917	979.9915	−0.0002
Madrid, Barajas Airport	979.9987	979.9987	0.0000
Sudan			
Khartoum Airport	978.3031	978.3031	0.0000
Sweden			
Göteborg, Torslanda Airport	981.7448	981.7442	−0.0006
Switzerland			
Geneva, Cointrin Airport	980.5888	980.5889	+0.0001
Zürich, Kloten Airport	980.6865	980.6865	0.0000
Tanganyika			
Dar es Salaam, Kurasini Airport	978.1169	978.1170	+0.0001
Thailand			
Bangkok, Don Muang Airport	978.3294	978.3292	−0.0002
Turkey			
Ankara, Etimesut Civil Airport	979.9501	979.9497	−0.0004
Izmir, Cuma Ovasi Airport	980.0234	980.0228	−0.0006

TABLE 3—*Continued*

Station	W10f	W147	Difference
	gal	gal	gal
Uganda			
Entebbe Airport	977.7238	977.7235	−0.0003
United States			
San Francisco, Travis Air Force Base	979.9896	979.9896	0.0000
Windsor Locks, Conn., Bradley Field	980.3487	980.3490	+0.0003
Chicopee, Mass., Westover Air Force Base	980.3555	980.3555	0.0000
Detroit, Mich., Willow Run Airport	980.3187	980.3187	0.0000
Princeton, N. J., Princeton University	980.1776	980.1778	+0.0002
Cleveland, Ohio, Airport	980.2323	980.2323	0.0000
Washington, D. C., National Airport	980.1089	980.1089	0.0000
Viet Nam			
Saigon, Tan Son Nhut Airport	978.2296	978.2297	+0.0001
Wake Island			
Airport	978.8804	978.8812	+0.0008
Yugoslavia			
Belgrade, Zemun Airport	980.6072	980.6072	0.0000

tions on which to base the comparison, and great importance is not placed on a few stations some of which may be at the extremes of the observed scatter in values.

Conclusions—This work has shown that over a five-gal. range the relative observational accuracy of two high-range geodetic-type Worden gravimeters, W-147 and W10f, is ±0.3 mgal., when the survey is carefully controlled. When calibrated on an absolute basis against modern pendulum measurements, such as those especially established for this purpose in North America, Africa and Europe, a similar accuracy of observed gravity is possible anywhere in the world.

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Gravity and Isostasy in Central Quebec

M. J. S. Innes

Abstract—A belt of intensely negative Bouguer and isostatic anomalies, nearly 140 mi wide, has been partially outlined in northern Quebec as a result of a regional gravity survey made in 1954. The axis of the belt trends northeast along the height of land and parallels the northern border of the Grenville geological province. The gravity minima are believed related to large masses of granite emplaced during a period of late Precambrian mountain building. The retention of these large anomalies for great periods of geologic time is discussed briefly with relation to isostasy and the strength of the crust and interior.

Introduction—This paper gives the preliminary results of a regional gravity survey carried out by the Dominion Observatory in northern Quebec during the summer of 1954. A total of 350 measurements were made at intervals of 10 to 20 mi over a large area (see Fig. 1 and 2) extending north from the St. Lawrence River between longitudes 64° and 72°, and as far as latitude 52° 40′. While most gravity stations lie within the Grenville geological province to the south, some lie within the Superior province [*Gill*, 1948*a*] to the northwest. Other stations in the northeastern portion of the surveyed area between Ashuanipi Lake and Mount Wright (Fig. 2), are not far from the southwestern extension of a belt of Proterozoic rocks, commonly referred to as the Labrador trough, which forms part of the Ungava geological province. The preliminary results of the survey reveal one of the most interesting gravitational features so far encountered in regional gravity studies of the Canadian Shield. Since this feature occupies a position within the border zone of three major geological divisions of the shield whose structural and age relationships are still unsolved problems of Precambrian geology, particular attention is given here to its description and possible geological and geophysical significance. Other interesting features of the regional gravity field are to be discussed in a later report, when additional field investigations have been completed.

General features of the gravity field—Contours of the Bouguer gravity anomalies are drawn on Figure 2 on which geological information from the *Tectonic Map of Canada* [1950] is also shown. The anomalies have a range of about 130 mgal, decreasing in intensity to the north, from small positive values near Sept Îles on the north shore of the St. Lawrence River. Over the greater portion of the map area to the southeast the anomaly contours exhibit no particular trend and are quite irregular, with gravity values varying from −60 to −40 mgal.

The most conspicuous feature of the gravity field is near the northern border of the survey, where the gravity contours take on a definite northeast trend and the anomalies become intensely negative. If the southern boundary of the disturbance is defined by the −60 mgal contour, it has already been traced for more than 300 mi and, although more measurements are needed to be certain, there is some indication that the low gravity values extend southwest another 150 mi to Lake Mistassini. In the opposite direction, to the northeast, the gravity minimum has been traced as far as Mount Wright and Ashuanipi Lake, near longitude 67° W.

From the data on hand the anomalies seem to form a belt-like pattern with minimum values established for over a hundred miles. The western portion of this gravity axis lies some 35 to 40 mi southeast and parallel to the boundary zone that separates the Superior and Grenville geological provinces and which is called the Grenville Front [*Derry*, 1950]. The latter, also known as the Huron-Mistassini Fault zone, cuts off abruptly the belts of Huronian-type (Proterozoic) rocks lying on its northwest side, from the Grenville complex to the southeast. Where the Huronian rocks are absent, the early Precambrian rocks of the Superior (Temiskaming-Keewatin) province are similarly terminated. The exact nature of the Grenville Front has not been fully agreed upon and its continuity has been questioned (*Lord*, 1949]. *Norman* [1936, 1940] advanced the idea that a zone of faulting extended all the way between Lake Huron and Lake Mistassini. This zone is believed by some [*Cooke*, 1947; *Wilson*, 1954, p. 192] to extend northeastward to the Labrador coast. According to *Derry* [1950] however, there is no known geological evidence for it between longitudes 64° and 70° W. Here the gravity results are not clearly defined, but to the northeast it is of interest to note that there is some indication that the gravity axis trends to the north and its projection inter-

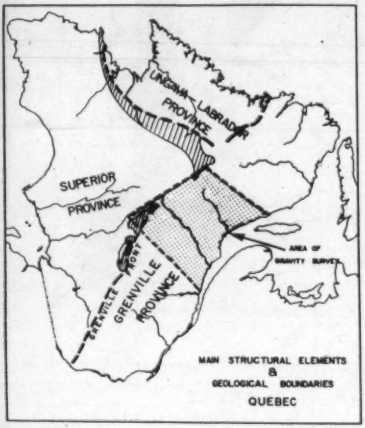

FIG. 1 – Principal structural units and geological boundaries, and region covered by survey

sects the rocks mapped as part of the Labrador trough.

The average Bouguer anomaly along the axis of the low, as far as established, is about −115 mgal, which is about 65 mgal lower than the average background value of the anomalies to the southeast. Figure 3 shows the gravity profile for the line A-B (see Fig. 2) and for its continuation southeast to Baie Comeau on the north shore of the St. Lawrence River. This line crosses the gravity axis at Courtois Lake, where the Bouguer anomaly is −128 mgal, the largest negative anomaly within the area and, incidentally, the largest so far recorded for the Canadian Shield. With respect to average values the decrease in gravity over the belt on this line is about −80 mgal, and the width of the gravity depression at least 140 mi.

Lest it be argued that the intensely negative Bouguer anomalies are largely due to isostatic compensation, isostatic anomalies were computed for seven stations along the gravity profile, using both the Pratt-Hayford and the Airy method of reduction. For the former a depth of compensation of 113.7 km was assumed; for the Airy method reductions were made by assuming crustal thicknesses of 20 km, 30 km, 40 km, and 60 km. The anomalies by all methods of reduction are collected in Table 1; the Pratt-Hayford isostatic anomalies are illustrated in Figure 3. The results show the region to the south, from Manuanis Lake to the St. Lawrence River, to be essentially in isostatic equilibrium, while the area to the northwest is over-compensated by as much as 77 mgal. Negative isostatic anomalies such as these point to large stress differences within the crust and are usually found to be associated with crustal disturbances that are geologically recent. It is rather surprising, therefore, to find such large anomalies in the Canadian Shield which, apart from broad warpings, [*Cooke*, 1931] is considered to have been a rigid and stable block since the end of Precambrian time.

Interpretation—The geology of this area has not been mapped in detail, but from the evidence available [*Low*, 1897; *Dresser* and *Denis*, 1944; *Derry*, 1950; *Rose*, 1955] the dominant rock types are granites, ortho- and para-gneisses including, in some places, masses of intensely metamorphosed sediments that closely resemble the Grenville series of the southeastern part of the shield. Remnants of younger rocks are also known to occur in down-folded areas at several locations along the southern flank of the gravity low, between Lake Pletipi and Mount Wright. According to exploration geologists working in the area, these younger rocks, which include iron-formation and other sedimentary rocks, chiefly marble and quartzite, are believed to be the metamorphosed equivalent of the Huronian type rocks of the Labrador trough [see also *Harrison*, 1955]. The negative gravity anomalies can only result from low-density masses within the crustal column and, although several hypotheses may be advanced, the most likely explanation seems to be that they result from large belt-like masses of intrusive granite that may or may not be exposed by denudation. The geological interpretation suggested is illustrated in Figure 4. The anomaly is considered as due to a direct contrast in density between massive granites of low density and the foliated granite gneisses, including the highly metamorphosed Grenville sediments.

Negative gravity anomalies associated with massive granites have previously been reported by *Miller* [1946], *Woollard* [1948], *Bott* [1953], *Marshall* and *Narain* [1954], and *Coron* [1954]. Similar relationships have been noted by the author for parts of the shield within the Superior geological province, where smaller but nevertheless quite intense negative anomalies form belt-like patterns over great distances. The proportion of intrusive granite to other rocks in this area is not definitely known, but summaries of the general geology [*King*, 1951; *Dresser* and *Denis*, 1944] sug-

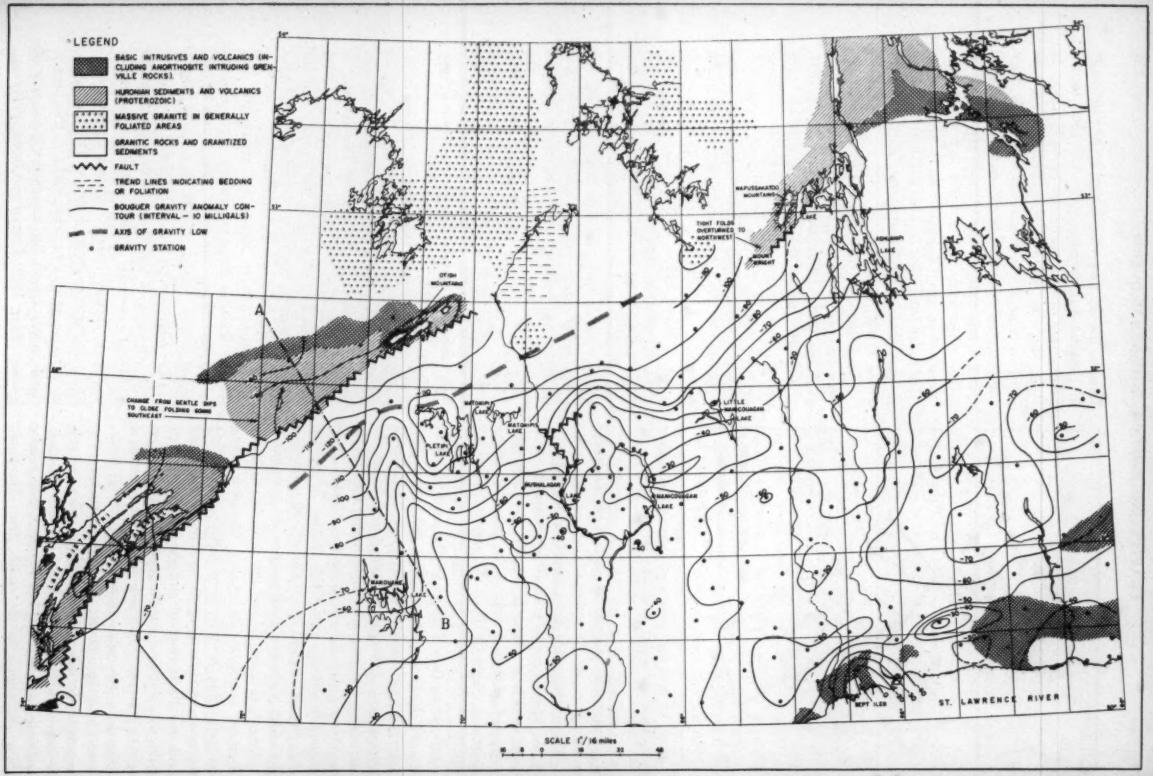

FIG. 2 – Bouguer anomaly contours and geological information

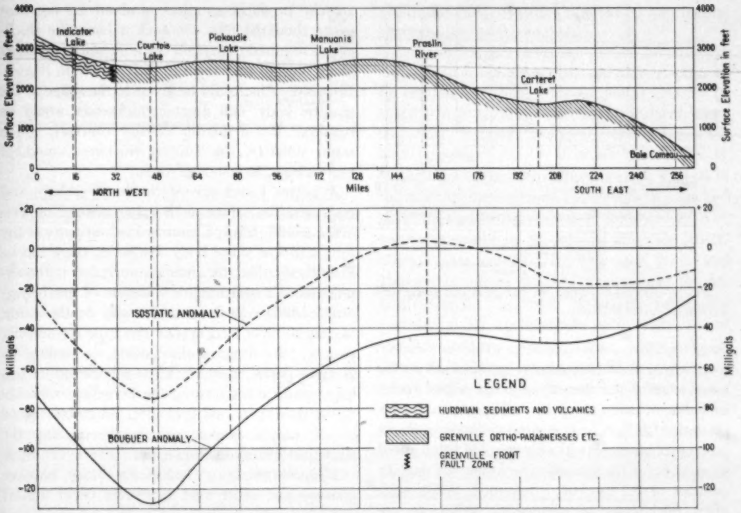

FIG. 3 – Elevation and anomaly profile for the line A-B and its extension to Baie Comeau

TABLE 1 – *Gravity anomalies by several methods of reduction for stations along a line crossing the negative anomaly belt*

Station	Elevation	Bouguer anomaly	Free-air anomaly	Isostatic anomalies				
				Hayford (113.7 km)	Airy			
					(20 km)	(30 km)	(40 km)	(60 km)
	ft.	*mgal*	*mgal*	*mgal*	*mgal*	*mgal*	*mgal*	*mgal*
Indicator Lake	1658	−95.7	−39.2	−48.2	−36.5	−40.8	−46.2	−51.6
Courtois Lake	1909	−128.8	−61.7	−76.9	−64.6	−68.7	−72.4	−78.7
Piakoudie Lake	1777	−91.7	−31.2	−44.6	−32.5	−36.6	−40.0	−46.2
Manuanis Lake	1597	−56.7	−2.3	−11.6	+0.8	−3.1	−7.0	−13.7
Praslin River	1810	−42.5	+19.1	+3.5	+15.4	+12.6	+8.5	+2.0
Carteret Lake	1125	−46.8	−8.5	−14.3	−3.4	−6.4	−9.7	−16.9
Baie Comeau	203	−23.9	−17.0	−11.4	−12.0	−11.3	−10.6	−10.9

gest that within the Grenville the granitic rocks become more continuous northwestward and finally dominate altogether immediately southeast of the Grenville Fault zone. Perhaps the strongest evidence is given by the tectonic map of Canada, which shows one large exposure of intrusive granite to be situated on the gravity axis (Fig. 2) and another along its extension to the northeast, directly west of Wabush Lake. The latter is described by *Gill* and others [1937].

No other interpretation of near-surface origin for the anomalies is quite so attractive as the one just given. A down-faulted basin or graben of sedimentary rocks might seem a possible solution, since the gravity axis is paralleled on both sides for a portion of its length by known or postulated faults. However, where the geology is better known, there is evidence that the Grenville rocks to the south of the fault zone have moved up, rather than down, relative to those to the northwest. While this may be sufficient evidence to eliminate the hypothesis of a down-faulted structure, the greatest difficulty is that no masses of low-density sedimentary rocks are known to exist in the area in sufficient quantities to satisfy the gravity data. As the number of gravity measure-

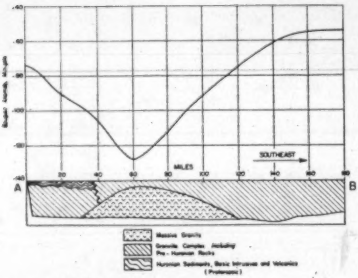

FIG. 4 – Anomaly profile for line A-B and suggested geological interpretation

ments increases, more and more evidence becomes available to show that massive granites are on the average less dense than the average crustal rocks, including those of some sedimentary basins [*Murphy*, 1952]. A basin having a minimum thickness of six miles near its center would be required to account for the anomalies here even if a density contrast of 0.2 gm/cm³ is assumed. While such great thicknesses of low-density sediments are highly improbable, the high grade of metamorphism exhibited by most rocks in the area suggests a smaller density contrast to be more likely. If this is so, correspondingly greater thicknesses would be demanded, making the hypothesis still less acceptable.

Accepting the interpretation that the greater part of the anomaly variation is controlled by masses of intrusive granite, what now can be said concerning the magnitude of the granitic body? While gravity anomalies alone are insufficient to determine uniquely the masses responsible for them, some information concerning the size and depth of the disturbance may be estimated from the amplitude, gradient, and width of the anomaly variation. For example, the maximum depth to the center of the disturbance is not likely to be greater than the horizontal distance over which the anomaly falls to half its minimum value, which in this case is about 35 mi. However, large anomaly gradients, as great as 3.3 mgal/mi, near Little Manicouagan Lake for instance, strongly suggest that the anomalies result from masses not deeply buried and which in some places may reach the surface.

A lower limit for the thickness of the intrusive granite may be obtained from the fact that an extensive horizontal sheet of matter differing in density from the material enclosing it by 0.1 gm/cm³ produces an effect of about 1.3 mgal for every thousand feet. On such a basis the thicknesses required to explain the anomalies for points along the axis vary from 10 to 12 mi (16 to 19 km). If consideration could be given to the shape of the granitic body, still greater thicknesses would be required. For a greater density contrast, which seems unlikely, the limiting thickness would, of course, be correspondingly less.

A better knowledge of the local geology and rock densities, along with other controlling evidence would permit a more refined estimate of the form and size of the body. However, there can be little doubt that the anomaly variation is the expression of a near-surface structure of great magnitude which extends to considerable depths within the crust. (The thickness of the crust for another part of the Precambrian shield, according to *Hodgson* [1953], is 36 km.) The significance of this large granitic body along the boundary zone between these two vast geological provinces should be of critical importance in determining the structural history of the region.

Mountain building hypothesis—Since massive granites and other acid intrusives occur almost exclusively in orogenic belts, the interpretation favored above would suggest that mountain building took place on a major scale along this portion of the Grenville Front. Probably the strongest evidence for this are the geophysical data, which show that the Bouguer anomaly field is not much different in amplitude and extent from that of younger and still quite high mountain ranges. The maximum amplitude, for instance, is about 28 mgal greater than has been observed throughout the Appalachian region (from a gravity-anomaly map supplied by G. P. Woollard) and is only 30 to 40 mgal less than the amplitude of the anomalies associated with the eastern Alps (Fig. 5) [*Holopainen*, 1947], or with the coast range of the Canadian Cordilleran region (Fig. 6). (The elevations shown in profile illustrate the maximum heights near the gravity traverse and are not necessarily those of the gravity stations). It is also important to note that the anomaly contours parallel the dominant structural trends and direction of folding of the Grenville rocks and that the width of the belt appears to be about the same as that of other orogenic belts.

Although no attempt is made here to present the geological evidence for mountain building along the northern boundary of the Grenville province, it can be stated that wherever the geology has been studied in sufficient detail, chiefly in areas to the southwest, there is much to suggest

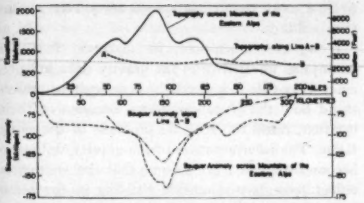
Topography across Mountains of the Eastern Alps
Topography along Line A-B
Bouguer Anomaly along Line A-B
Bouguer Anomaly across Mountains of the Eastern Alps
KILOMETRES
500 KILOMETRES

FIG. 5 – A comparison of the elevation and Bouguer gravity profiles for the eastern Alps and the line A-B

that the border zone was part of a block subjected to mountain-building forces during late Precambrian time [*Quirke* and *Collins*, 1930; *Norman*, 1940; and others]. It should also be mentioned that the exact nature of the disturbance has not been fully agreed upon; there is doubt as to whether the truncation of the east-west folding of the Superior province by the Grenville complex to the southeast is due to faulting or to large-scale failure of the crust and major orogeny [see *Cooke*, 1947; *Gill*, 1948ab; *Wilson* 1948; and *Lord*, 1949 for summaries and discussions relating to this problem].

One might expect that the former Precambrian mountains would have been completely removed by erosion, but there is topographical evidence to suggest that remnants of this postulated range still exist. Although the local relief is somewhat higher to the south, the drainage through deeply cut valleys is also in that direction and the axis of the gravity low more or less coincides with and parallels the height of land (Fig. 1 and 2). The region generally forms part of the wide central plateau that separates the basins of James and Hudson Bay from those of Ungava and the Atlantic Ocean. The Otish Mountains border the plateau on its northwestern side, while Mount Wright and the Wapussakatoo Mountains lie along its southeastern margin. These mountains, which might better be described as hills or ridges, are, nevertheless, still prominent topographic features which rise several hundreds of feet above the general level of their surroundings. They are capped by highly resistant rocks, chiefly massive

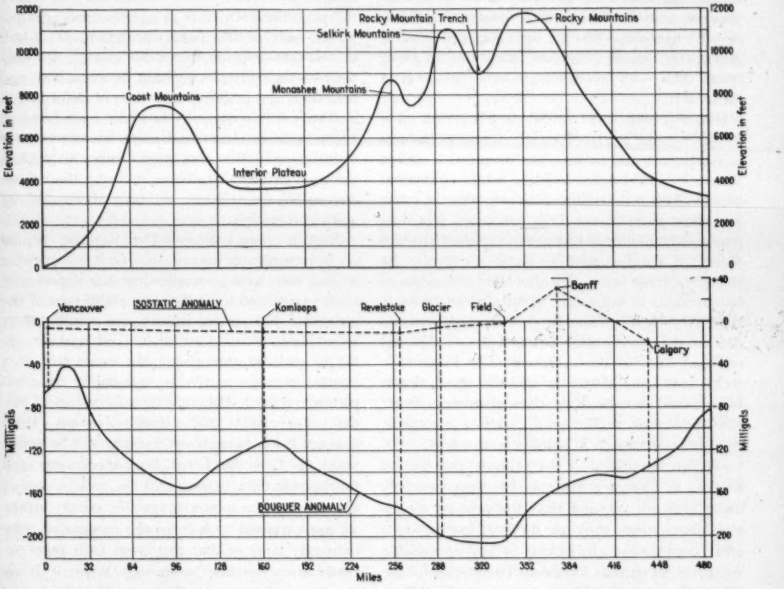

FIG. 6 – Bouguer and isostatic anomaly profile across the Canadian Cordillera

quartzites, which probably accounts for their preservation.

It may be of considerable geological significance that these prominent topographic features that constitute part of this postulated range are also a part of the two belts of Huronian-type rocks in the area, one lying to the northwest of the Grenville Front and the other forming the southwestern tip of the Labrador trough. This, together with the evidence that the intensity of folding and faulting increases in a direction towards the gravity axis (Fig. 2), strongly suggests that these belts were once continuous as part of a geosynclinal belt to the south and east of the Superior province, which later was subjected to intense deformation, mountain building, and igneous intrusion, and that subsequent uplift and erosion have reduced it to its present position.

Such a hypothesis is by no means original. A similar one was advanced years ago by *Quirke* and *Collins* [1930], who considered that the gneisses and sediments of the Grenville complex in the Georgian Bay area were the more highly metamorphosed equivalent of the Huronian rocks. Chiefly because of the discovery of the great fault zone separating these areas of contrasting lithology the hypothesis has not been accepted by most geologists; recently, however, according to *Derry* [1950] there is an increasing amount of evidence in favor of it.

Wilson [1948, 1951, 1954] as the result of a comprehensive study of major structural features of continents and oceans, has proposed a unified theory of mountain building and continental growth. It is rather difficult to reconcile the interpretation given above with his views regarding mountain building in this portion of the Canadian Shield. If I understand his theories correctly, he considers these belts of Proterozoic sediments to be remnants of secondary mountains in the sense that they were formed from erosional products deposited upon an older foreland or a stable and resistant shelf of the continent. The Proterozoic rocks near Lake Mistassini and the Otish Mountains would thus be derivatives of primary Grenville mountains to the south, while the rocks of the Labrador trough [*Cumming* and others, 1955] would be secondary to the primary province of Ungava or Labrador. He considers that secondary mountains are younger than the primary mountains from which they are derived, extend to no great depths, and are lacking in any appreciable volcanism or igneous intrusion. The Rockies of the North American Cordillera are believed by Wilson to be a more recent example of secondary mountain building.

If we are to suppose, for instance, that the mountains inferred from the gravity data are primary Grenville mountains, it is difficult to understand how the Huronian rocks, because of their location, could be erosional products of the same range. The interpretation of the gravity data also becomes difficult if we assume that the anomalies reflect secondary mountain building in the sense described by Wilson. The outstanding objection in this case is that the gravity data suggest intense deformation of the crust and granitic intrusion on a major scale, both of which are inconsistent with the postulates of Wilson's theory.

There is little point in further speculation at this stage, as the full significance of this negative anomaly belt is not likely to be realized until its full extent has been measured and until more complete geological information is available. It should be mentioned, however, that elsewhere in the Grenville province, where the geology is better known, no outstanding gravitational effects such as these have been observed [*Thompson* and *Garland*, in press] and it may be necessary to regard this postulated structure as a phenomenon characteristic only of this particular region. It is well known that orogenic belts differ greatly, not only between themselves but within the same belt, and that both the intensity and time of deformation may vary within relatively small distances (*Bucher*, 1933]. A more recent and more intense tectonic disturbance in this area might suffice to explain the large gravity disturbance and why the masses responsible for it have not been eliminated by uplift and erosion.

Isostatic considerations—The isostatic results are of considerable interest because it is surprising to find such large anomalies within a region generally considered to be the most stable part of the continent. For perfect isostasy one would expect reduction in altitude by erosion and isostatic uplift to proceed throughout the entire life of a mountain range until its topography is completely removed. Although there is geological evidence to indicate [*Gill*, 1948b; *Johnson*, 1954] that uplift has taken place and may still be active along the Grenville Front, both the gravity and topographic data suggest that the greater part of the 'root' of the former range still exists (unless we are prepared to believe the mountains were unusually large or that they were built more recently than generally supposed). When it is remembered that nearly 10^9 years [*Cummings* and

others, 1955] have elapsed since mountain building is believed to have taken place within this part of the Precambrian shield, it is not difficult to conclude that uplift and erosion here have been much slower than is demanded by isostasy.

The isostatic anomalies along the Grenville Front have been related to direct density differences between highly metamorphosed sediments and gneisses on the one hand and masses of intrusive granites on the other. It seems worth while to mention that, if conditions similar to these exist deep within younger mountains, much of the gravity disturbance associated with them and usually attributed to compensation in the form of a bulge at the lower boundary of the crust, may in reality be due to large masses of intrusive granite within the crust.

The isostatic anomalies are also shown in Figure 6 for those stations on the traverse across the Canadian Cordillera for which reductions have been made [*Miller*, 1929]. These and the large measure of correlation between heights and Bouguer anomalies show these younger mountains to be compensated. Some differences, however, which may be related to the amount of igneous activity associated with their formation may be noted. The mountains west of the Rocky Mountain Trench all contain a large proportion of intrusive rocks and seem to be well compensated. The Rockies, on the other hand, are characterized by great thicknesses of sediments and few exposed intrusives, and are believed to be without roots. In support of this view it is noted that the isostatic anomaly at Banff is positive, which implies that the mountains there are loads upon the crust. They are not, however, completely lacking in isostatic support, for it is also noted that the anomaly near Field, B. C., is almost zero. Regarding the Eastern Cordillera as a whole, *Lang* [1948] points out that while no batholithic core has yet been revealed, this range is in its first cycle of erosion, and there is evidence that the orogeny which formed it was accompanied by igneous activity.

The close association between igneous activity and mountain building, together with the fact that younger mountains are found to be fully compensated while older ranges are not, suggests that the emplacement of granite batholiths, the formation of mountains and their isostatic adjustment are intimately related and simultaneous processes, resulting from the same causes operating deep within and below the crust. This would imply also that the mechanism by which mountains are compensated is a compromise between the two fundamentally different hypotheses, the one advanced by Airy and the other by Pratt. The conditions seem consistent with the former only in so far as part of the gravity disturbance may reflect regional compensation or a general thickening of the crust under continents. They are consistent with the Pratt hypothesis in that the mountains are locally compensated and stand higher because of their lower than average crustal density.

It is generally realized that the actual conditions and mass distributions within the crust are much more complicated than is assumed by either of these classical theories of isostasy. However, evidence of large masses of low-density material high within the crustal column under mountains has the interesting implication that a much smaller 'root' structure at the lower boundary of the crust would be required to explain the gravity disturbance than is usually demanded.

Although near-surface irregularities in density of small horizontal extent may cause disturbances in gravity that bear little or no relation to the general isostatic condition of a region, the anomalies along the Grenville Front keep the same sign over great distances (the width of the belt appears to be at least 220 km). The masses responsible for them may reach the surface in places but also extend to great depths within the crust. The anomalies, therefore, imply real (negative) loads which must be supported by the fundamental strength of the crust and the interior. *Jeffreys* [1952] has shown that the greatest stress difference due to a mountain chain in the form of a raised triangular strip is about equal to one-half the range of its load and that the strength required to support it must be available at a depth about equal to one quarter the width of the chain. If the structure implied by these isostatic anomalies can be so approximated, a strength of about 9×10^7 dynes per cm^2 at a depth of nearly 56 km is required to support the unbalanced load.

It has been estimated [*Jeffreys*, 1939, 1952] from several lines of evidence that stress differences of at least 1.5×10^9 dynes per cm^2 exist within the outer 50 km of the Earth, decreasing to about 1.5×10^8 between depths of 50 to 600 km. If these estimates are correct, it would seem that unbalanced loads as great as those implied by the above gravity anomalies could be supported almost indefinitely without isostatic adjustment occurring. On the other hand, it has already been stated that there is evidence that the crust in this region is rising or has done so in the recent past.

Summary—A belt-like pattern of intensely negative gravity anomalies that parallels the northern border of the Grenville geological province in northern Quebec is believed to reflect batholiths of massive granite that probably intruded during mountain-building activities of the late Precambrain. Considering the great size of the postulated 'root' structure and its probable age, it would appear that the rate of uplift and erosion has been much slower than usually thought. The position of belts of Proterozoic sedimentary rocks relative to the gravity minima suggest that these rocks were also involved in the orogeny that emplaced the granite.

When taken all together, the evidence seems consistent with the concept of a strong crust accompanied by a measure of broad regional compensation. It suggests that igneous intrusion, the formation of mountains, and their compensation are simultaneous processes; and that much of the gravity disturbance associated with mountains and usually attributed to crustal thickening under them might reasonably be explained by horizontal variations in density within the crust. Stress differences estimated from the gravity information do not seem large enough to maintain the subcrustal flow necessary for isostatic adjustment, although there is evidence for crustal uplift along the Grenville Front.

Considerably more gravity data as well as geological information are needed before the interpretation suggested above can be accepted with any finality, but it is hoped that this paper may stimulate further investigation by increasing interest in the area.

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A Field Installation for Automatic Recording of Micro-environmental Gradients

ROBERT B. PLATT

Abstract—A laboratory has been constructed in the field with a design sufficiently basic and flexible to permit correlation of micro-environmental conditions with distribution and abundance in space and time of a wide variety of plants and animals. Two 50-ft wooden towers, located at ecological extremes of a dense woodland and an open field, have been equipped with instruments for automatic recording of micro-environmental gradients. Aminco-Dunmore-type electric humidity and temperature indicators have been placed at the 0, 3, 6, 15 and 50 ft levels, and temperature elements only at the 1, 16, 18 and 36 inch soil depths, each complete set being fed into a 16-point strip recorder. Special weather shields have been designed for the humidity-temperature indicators. Recording anemometers are at the 3 and 50 ft levels, and recording rain and surface water level gages are near the base of each tower. Portable instruments provide for supplementary environmental data on radiation, light, wind, temperature and humidity.

Introduction—A laboratory has been constructed in the field with a design sufficiently basic and flexible to permit correlation of micro-environmental conditions with distribution and abundance in space and time of a wide variety of plants and animals. Organisms studied to date have been arthropod vectors of disease, particularly mosquitoes. Collections made in different habitats at various elevations for successive intervals through the night over a period of two years demonstrate that not only do various species of mosquitoes have their own patterns of distribution and abundance, which may vary from night to night, but that these patterns also shift through the night both vertically and horizontally. The experimental design is based on this two year preliminary study. The environmental aspects of this have been presented by *Platt* and *Goodwin* [1957]. A general account of the project has been given by *Platt* [1955]. The installation has been in satisfactory use since October, 1955.

Instrumentation and methods—Two 50-ft wooden towers (Fig. 1), located at ecological extremes of a dense woodland and an open field, have been equipped with instruments for automatic recording of vertical and horizontal environmental gradients. The large platforms are requisite for collection of biological data. Both collection devices and sensing elements are located on booms which position them away from the tower and thus reduce possible effects the tower might have on results obtained.

Full range humidity-temperature sensing elements have been placed at the 0, 3, 6, 15 and 50 ft levels (corresponding to vegetation levels), and temperature elements only at the 1, 6, 18 and 36 inch soil depths, each complete set being fed into a 16-point strip recorder. An interval timer, placed between the elements and the recorder, limits the readings to one complete cycle of eight minutes for each 30-min interval. Moisture is expressed as vapor pressure, absolute humidity, or relative humidity.

The environmental factor which posed the greatest instrumentation difficulties was that of atmospheric moisture. After reviewing all types of sensing elements, an electrical hygrometer (Aminco-Dunmore type-8 TH-2, American Instrument Co.) was chosen because it best conforms to the following conditions considered requisite to this particular project. (a) It covers the relative humidity range from 6–99 pct at 80° F with a declared accuracy within ±1.5 pct relative humidity. When checked in the field against a Model-7000 dew pointer (Illinois Testing Laboratory), day to day variations of individual elements were less than one per cent. Although organisms may not be able to detect humidity differences of this degree, such sensitivity is mandatory, if vertical and horizontal gradients are to be satisfactorily determined. Figure 2 demonstrates this by showing the humidity gradients obtained for one month at 03h 00m and at 15h 00m for both the woods and the field. (b) The sensing elements are in continuous equilibrium since their speed of response of 65 pct of a total change within 12 sec is faster than changes which occur naturally. (c) The incorporation of temperature sensing elements within the relative humidity units provides for recording of temperature and humidity on the same recorder. (d) The recording of temperature and relative humidity indications for each element within 30 sec of each other enhances the accuracy

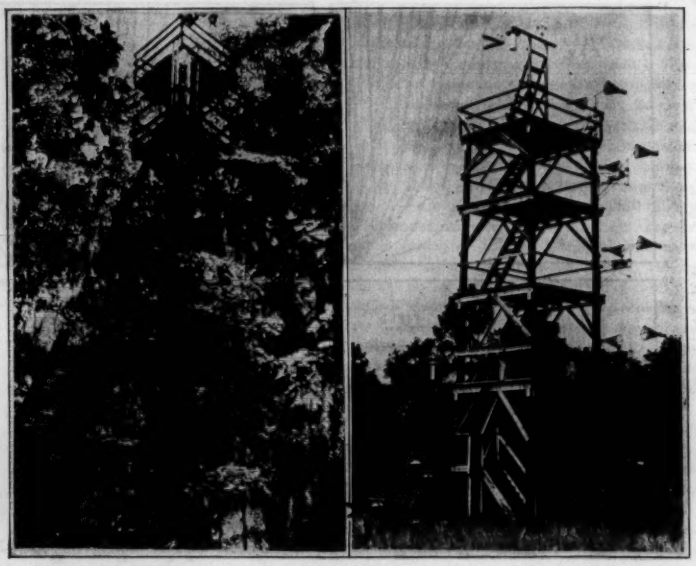

FIG. 1 – Fifty-foot wooden towers showing U. S. Forest Service design at left and our later design at right; on the field tower, humidity-temperature shields are indicated by pointers and the recorder is in the box on the first platform; for entomological data, mechanical sweep nets show at the right, and light traps are located on the far side; for other instrumentation, see text

of calculating absolute humidity and vapor pressure. (e) The complete system of matched sensing elements and recorders is commercially available.

The decision was made not to aspirate the humidity elements. Since the accuracy of the elements without a constant air movement is adequate, then any accuracy which might be added by aspiration would be of dubious value, because of the added problems of instrumentation, and especially because of the fact that the unnatural air currents produced by aspiration may create errors greater than the gradient itself. *Tanner* and *Soumi* [1956], in measuring small vapor pressure gradients above a crop with a Foxboro Dewcel, solved this problem of aspiration without producing adverse air currents by rotating air intake nozzles over the crop surface for a distance of 50 to 60 ft, the air being exhausted across the sensing elements away from the field.

The next problem was to find a way to shield the humidity elements from the weather, especially rain and radiation, the elements being designed for indoor use. The temperature elements posed no particular problem inasmuch as they were located inside the humidity element cases. Since suitable weather shields could not be found in the literature, one was designed for this particular installation (Fig. 3). The relatively mild weather conditions of southern Georgia did not justify the use of a shield such as that designed by *Conover* [1950] for use with a Foxboro Dewcel for the rigorous weather conditions prevailing at the Blue Hill Observatory near Boston.

The weather shield consists of a 9 × 20 inch cylinder and a 20 inch top, made of 22 gage #7 mirror-polish stainless steel, painted dull black on the interior. Wire brackets, not shown in the Figure, provide for guying it firmly to the ground.

Performance under varying conditions of insolation and wind was determined in the laboratory. A horizontal unidirectional infrared radiation intensity at the cylinder surface of 1.5 K cal/sq cm min was directed horizontally at the cylinder surface. Although this is equivalent to high summer sunlight intensity it is much greater than that actually received, since direct sunlight can only

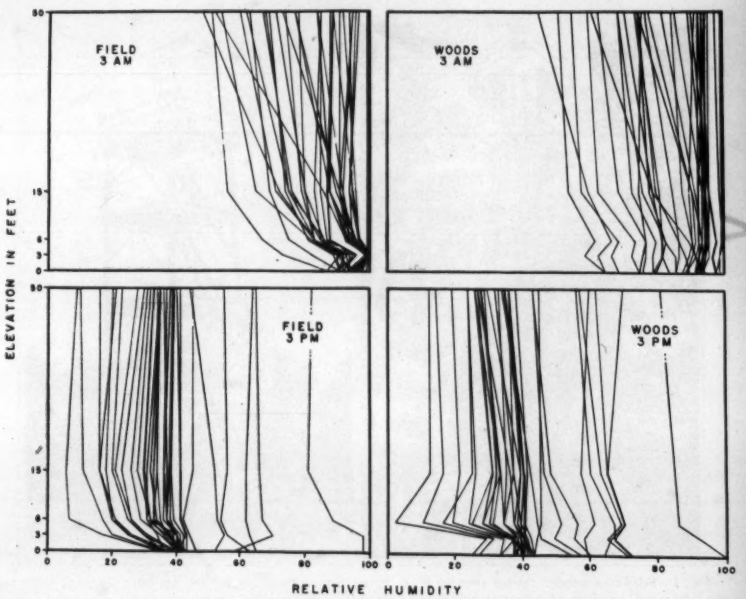

FIG. 2 – Vertical relative humidity gradients obtained from May 15 to June 15, 1956, for both woods and field at 03h 00m and at 15h 00m from 0 to 50 ft elevation

strike the sides of the shield in the early morning or late afternoon. The air temperature between the heated side and the sensing elements rose in 40 min to an equilibrium of 13° F above an ambient temperature of 84° F, while that between the sensing element and the opposite side rose only 3.5° F above ambient. This is 7° F and 2° F, respectively, lower than results obtained using a matt finish stainless-steel cylinder. Convection currents in the cylinder, as determined by a thermo-anemometer with a ¼-inch diameter probe, varied from 15 to 25 ft/min across the bottom, and from 14 to 50 ft/min across the top. Assuming an air movement into the cylinder of 20 ft/min, the air inside will be changed every five seconds. When a horizontal air current of 500 ft/min is introduced the air movement upwards, despite considerable turbulence, is increased by at least a factor of 4.

With the same surface intensity of 1.5 K cal/sq cm min directed vertically against the top as would occur at noon, the temperature around the sensing elements reached an equilibrium in 30 min of only 2° F above ambient. Air movement through the cylinder was slower, being 13–20 ft/min across the bottom, and 11–25 ft/min across the top.

In order to simulate windy conditions without radiation, an air movement of 500 ft/min was directed horizontally at the shield. Although, in the absence of convection currents, turbulence was increased inside the shield, the net direction of air movement was upwards, as determined by use of smoke.

These data may be evaluated as follows. (a) When air movement or differentials of temperature occur, the air sampled is that entering the lower end of the cylinder. The elevation of each element is therefore determined by measurement from this part of the cylinder, the shield for the surface layer of air being, for example, two inches above the ground. (b) Under field conditions, temperature and corresponding humidity errors can be imposed by the shield only during the morning and afternoon hours, when the cylinder is heated laterally by the Sun. Field measurements indicate an increase of usually not over 2–3.5° F on clear

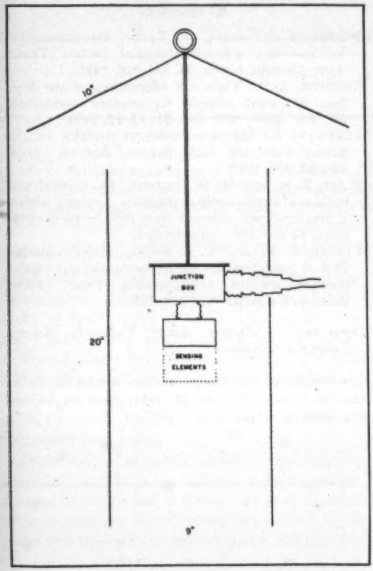

FIG. 3 – Diagram of weather shield; wire brackets for suspending cylinder from upper cone, and guy wires at base are not shown

summer days, resulting in a maximum relative humidity error of two or three per cent depending upon ambient conditions. Such infrequent errors are not significant in our work, since they occur between the times of maximum gradients and early afternoon extremes.

The soil-temperature sensing elements are matched thermistors of the same type used for air temperature. The lead for each is a two-conductor no. 14 gage weatherproof cable, the sensing element being sealed at the end with an embedding type thermoplastic.

Wind, rain, and surface-water determinations are also recorded for each tower. Anemometers, at the top as well as at the three-foot level near the base, are read at various intervals as determined by experimental conditions. Recording and can-type rain gages, and recording surface-water level indicators are serviced weekly.

A number of portable instruments provide for obtaining supplementary environmental data. Black and white Livingston atmometers were installed in the preliminary study in five vertical series, on and adjacent to the towers, for several months at a time, and although not installed now, are available for further use when needed. These provide an evaporativity index of the atmosphere. Heat intensity or solar radiation may be determined by a type-DW-68 General Electric total radiation meter; light, by several kinds of photometers reading up to 20,000 foot candles intensity; air movement, especially convection currents and movement in small places, by a type-8500 thermo-anemometer with a one-quarter inch diameter probe made by Illinois Testing Laboratories; humidity, by a type-7000U Dewpointer, also by Illinois Testing Laboratories; and temperature by various sensing elements, including 0.4 mm diameter thermistor beads for either contact or small area measurements. Additional instruments, as for example, those which better indicate heat flow conditions in the environment, may be added as needed [*Brooks* and *Kelly*, 1951].

Routine personal observations, recorded daily on a special data form, include sunshine and sky conditions, kind of rain, direction and character of wind, times of sunrise and sunset, and moon phases.

The reference framework with which these local meteorological observations may be correlated is provided by first-order Weather Bureau stations maintained at Atlanta, Georgia; Tallahassee, Florida; and Montgomery, Alabama, since the installation is located near the center of a triangle made by these three cities. A Class A Weather Bureau facility is maintained by the Field Station eight miles from the installation.

The first phase of data manipulation has been to investigate possible correlations existing between the specific movement and distribution of particular species of mosquitoes and environmental conditions. The installation is designed to provide positive answers to such correlations. Therefore all analyses to date have consisted of detailed single and multiple factor correlations of mosquito collections, obtained hourly at various elevations by both attractant and non-attractant devices, with comparable environmental data. Although the mechanically and electrically recorded environmental data are obtained continuously, the rest of the environmental data and the entomological data are obtained for usually two nights per week, and detailed data analyses so far have been made only for these times. Special calculators and data forms have been designed to facilitate the work. IBM cards have been used for all entomological data, and provisions have been made to transfer

the environmental data to IBM cards for the second phase of the work. Encoders will be used to facilitate this transfer.

The second phase, now beginning, will be to attempt to establish statistically valid predictive environmental criteria for mosquito behavior from the cause and effect relationships obtained by the first phase.

Acknowledgments—This project is sponsored by Emory University and the Communicable Disease Center of the Public Health Service, the installation being located at their jointly operated Field Station in Baker County, southwest Georgia. The development of this installation has been possible only through the active cooperation of many people, especially Melvin H. Goodwin, Jr., Director of the Field Station, Robert Lofton, construction engineer, who built the primary facilities of the laboratory, and the American Instrument Company, especially C. H. Ellison, Sales Engineer. Partial support was provided by a research grant E-545 from the National Institute of Allergy and Infectious Diseases of the National Institutes of Health, Public Health Service.

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The Transport of Sand by Wind

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Abstract—The problem of the motion of an individual sand grain in wind is subjected to a physical-mathematical analysis. An empirical equation is obtained for observed wind-velocity profiles near the ground. The behavior of a sand grain in such a wind velocity gradient is assumed to be the result of three principal forces: the viscous drag of the air, the force of gravity, and the aerodynamic lift. Differential equations are set up on this basis. When solved by approximate methods for an average sand grain and for the profile obtained in a small wind tunnel, these equations give sand grain trajectories that agree fairly well with the trajectories observed and photographed in the wind tunnel.

Introduction—This project originated as a mathematical inquiry into the shape and movement of sand dunes. A small wind tunnel was constructed and it was found that moving miniature sand dunes could be produced artificially, but the mathematical problem proved complicated. The present report deals only with the first part of this problem, the analysis of the motion of an individual sand grain.

Theoretical: The model system.—Consider an irregular particle suspended in a fluid moving parallel to the ground in such a way that the fluid at any particular height above the ground has a constant velocity in the direction $+x$. Replace the particle by a sphere of equivalent radius, α. Call the fluid velocities at heights corresponding to the top, center, and bottom of the sphere V_T, V, and V_B, respectively. Assume for convenience that α is small enough that the velocity gradient in the fluid in the vicinity of the particle is linear

$$V = (V_T + V_B)/2 \quad (1)$$

Horizontal force acting on the particle—If the particle be considered to react as if suspended in a stream of uniform velocity equal to V, then, from Stokes' law, the force on the particle in the direction $+x$

$$F_x = 6\pi c\eta\alpha(V - S_x) \quad (2)$$

where V is the average velocity of the fluid flow in the vicinity of the particle, S_x is the velocity of the center of the particle in the direction $+x$, η is the coefficient of viscosity of the fluid, and c is a correction factor introduced because the particle actually is not a sphere.

Vertical forces acting on the particle—The total force acting on the particle in the direction $+y$

$$F_y = L + D_y - F_G \quad (3)$$

where L is the aerodynamic lift, D_y is the vertical viscous drag, and F_G is the force due to gravity.

The terms of (3) will be considered in reverse order.

The force due to gravity

$$F_G = gM(\rho_P - \rho_F)/\rho_P, \quad (4)$$

where g is the acceleration due to gravity, M is the mass of the particle, ρ_P is the density of the particle, and ρ_F is the density of the fluid.

The vertical viscous drag is found, by a method similar to that used in obtaining (2), to be

$$D_y = -6\pi c\eta\alpha S_y \quad (5)$$

where S_y is the velocity of the center of the particle in the direction $+y$, that is, perpendicular to the ground.

The derivation of an expression for the lift L will be based on a law of aerodynamics known as the Kutta-Joukowsky law, which states that the aerodynamic lift on a cylindrical body immersed in a moving fluid

$$L = B\rho_F V'\Gamma \quad (6)$$

where B is the length of the cylindrical body, V' is the average fluid velocity in the vicinity of the particle relative to the particle, and Γ is the circulation.

In the case of the circular cylinder

$$\Gamma = 2\pi\alpha V_P \quad (7)$$

where V_P is the peripheral velocity of the cylinder.

Since the body under consideration is not a cylinder, but a roughly spherical particle, it will be assumed that a correct expression for the circulation can be obtained by introducing a numerical constant k. In this case V_P becomes the peripheral velocity of the particle at the equator of the particle, and B in (6) becomes 2α.

V_P is found by assuming that the particle has so little angular inertia that it rotates at all times so that

$$V_T^1 - V_P = V_B^1 + V_P$$

or

$$V_P = (V_T^1 - V_B^1)/2 \tag{8}$$

where V_T^1 and V_B^1 are the fluid velocities relative to the particle at the top and bottom of the particle.

Putting (8) and the correction factor k in (7), the circulation

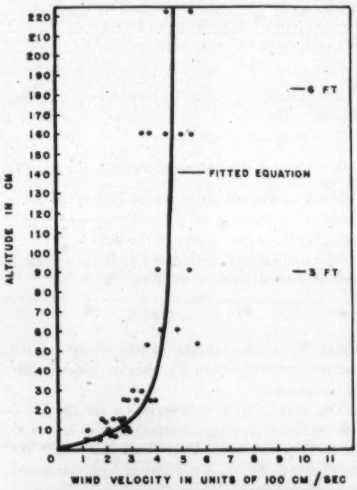

FIG. 1 - Experimental wind velocity profile

$$\Gamma = \pi k\alpha(V_T^1 - V_B^1) \tag{9}$$

It may now be noted that

$$V_T^1 = V_T - S_x,\ V^1 = V - S_x,$$

and

$$V_B^1 = V_B - S_x \tag{10}$$

Using (1), (9) and (10) in (6), and making the substitution $B = 2\alpha$

$$L = \pi k\rho_F\alpha^2[(V_T^2 - V_B^2) - 2S_x(V_T - V_B)] \tag{11}$$

A result similar to (11) can be obtained by an application of Bernoulli's theorem, if it is assumed that the lift is proportional to the difference in pressure between the top and bottom of the particle.

Putting (4), (5), and (11) in (3), the total vertical force acting on the particle

$$F_y = \pi k\rho_F\alpha^2[(V_T^2 - V_B^2) - 2S_x(V_T - V_B)] - 6\pi c\eta\alpha S_y - gM(\rho_P - \rho_F)/\rho_P \tag{12}$$

The equations of motion of the particle—It can be set down at once that $S_X = dx/dt$, $S_y = dy/dt$, $Fx/M = d^2x/dt^2$, $Fy/M = d^2y/dt^2$, and $M = \frac{4}{3}(\pi\alpha^3\rho_P)$. Making the appropriate substitutions, (2) and (12) become

$$d^2x/dt^2 = P(V - dx/dt) \tag{13}$$

and $d^2y/dt^2 = Q[(V_T^2 - V_B^2) - 2(V_T - V_B)dx/dt] - P\,dy/dt - g(\rho_P - \rho_F)/\rho_P$

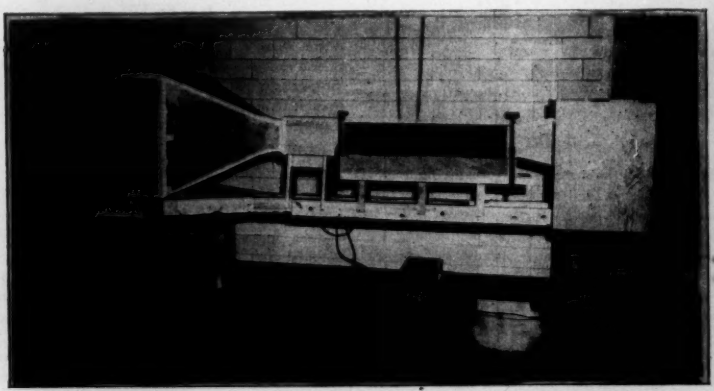

FIG. 2 - The wind tunnel

where

$$P = 9c\eta/(2\alpha^2\rho_P) \text{ and } Q = 3k\rho_P/(4\alpha\rho_P). \quad (14)$$

Experimental data—To calculate the trajectory of a sand grain in air moving over a plane surface from (13) and (14), it is necessary to assign a mass and equivalent radius to the sand grain, and to determine an expression for the wind velocity profile through which the sand grain is moving.

Figure 1 is a wind velocity profile obtained over a gravel surface with a small rotary anemometer.

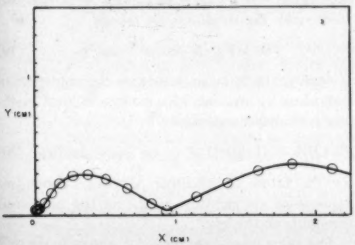

FIG. 3 – The theoretical trajectory of an average sand grain in the wind velocity profile in the wind tunnel observation chamber

It was found that such experimentally determined wind profiles could be fitted by empirical equations of the form

$$V = \overline{V}y/(y + A) \quad (15)$$

where V is the wind velocity at height y, $\overline{V}$ is the wind velocity at an infinite height (that is, ten feet), and A is a constant. This form of equation gives an approximately linear velocity gradient at low values of y, and velocities closely approaching $\overline{V}$ at high values of y, and appears to be adequate to describe the wind-velocity profile in the region which was primarily under consideration; that is, up to about a meter above the ground. However, if greater heights were involved, a logarithmic wind-velocity distribution such as used by *Zingg* and *Chepil* [1950] would probably be a better approximation. The profile shown in Figure 1 is fitted by the equation

$$V = 500\, y/(y + 10)$$

Here y is in cm, V in cm/sec.

The first two centimeters of a wind velocity profile obtained in the observation chamber of a small wind tunnel (Fig. 2) were fitted very well by the equation

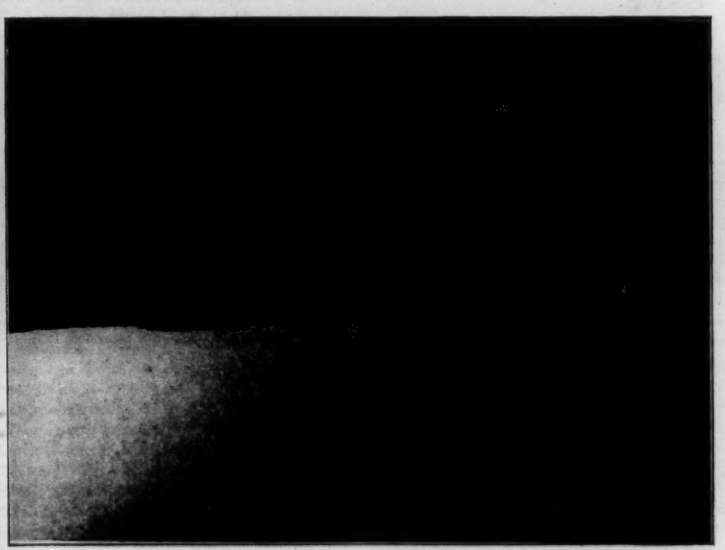

FIG. 4 – Sand grain trajectories photographed in the wind tunnel observation chamber

$$V = 868\, y/(y + 0.12) \qquad (16)$$

Since observation showed that most sand grains never reached a height of more than one centimeter in the observation chamber, (16) was used in calculating trajectories.

Building sand sieved to pass a 20-mesh screen and to be retained by a 40-mesh screen was used. The average weight of such sand grains was found to be 0.000333 gm. Assuming a density of 2.3, this makes $\alpha_{Av} = 0.0326$ cm.

Applications—Making

$M = 0.000333$ gm
$\alpha = 0.0326$ cm
$\eta = 0.000185$ poises
$\rho_P = 2.3$ gm/cm^3
$\rho_F = 0.001205$ gm/cm^3
$g = 980$ cm/sec^2
$k = 0.9$
$c = 1.2$
$V = 868y/(y + 0.12)$, $V_T = 868(y + \alpha)/(y + \alpha + 0.12)$, $V_B = 868\,(y - \alpha)/(y - \alpha + 0.12)$, all applicable to the wind tunnel experiment, and letting
$(\rho_P - \rho_F)/\rho_P = 1$ (actual value, 0.99947), then in equations (13) and (14),
$P = 0.409$,
$Q = 0.01085$,

and the equations of motion of the sand grain become

$$d^2x/dt^2 = 0.409\,(V - dx/dt), \qquad (17)$$

and $d^2y/dt^2 = 0.01085\,[(V_T^2 - V_B^2)$

$$- 2(V_T - V_B)\,dx/dt] - 0.409\,dy/dt - 980. \qquad (18)$$

The path of the center of the sand grain was calculated from (17) and (18) by a process of numerical integration. The result is shown in Figure 3. In this case the particle starts from an initial position at which $x = 0$, $y = 0.0326$, $dx/dt = 0$, and $dy/dt = 0$. Time increments of 0.01 second were used. The second portion of the plot shown in Figure 3 is based on the assumption of a perfectly elastic rebound at a time of 0.116 sec.

This trajectory agrees fairly well both in arching form and order of magnitude with the trajectories observed and photographed in the wind tunnel observation chamber using the sand and the wind velocity profile specified above. Figure 4 is one such photograph.

The condition that a particle be lifted off the ground can be obtained from equation (14) by noting that when the particle is at rest on the surface $dx/dt = 0$, $dy/dt = 0$, and $V_B = 0$. Eq. (14) then yields the condition for takeoff

$$(3k/4)V_T^2 > \alpha g(\rho_P - \rho_F)/\rho_F. \qquad (19)$$

Jeffreys [1929] in an article on the transport of sediments by streams, obtains by different methods a condition equivalent to

$$(1/12)[1 + (1/3)\pi^2]V_T^2 > \alpha g\,(\rho_P - \rho_F)/\rho_F \qquad (20)$$

for the lifting of spherical particles. These two expressions are identical except for the numerical constants on the left.

The value taken here for c, 1.2, agrees fairly well with the results obtained by *Kunkel* [1948] in an experimental study of errors produced by shape factors in Stokes' law estimates of particle radius. No data could be found on the value of k. The value taken, 0.9, was used because it gave particle trajectories of about the correct height.

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A New Model of Magnetic Storms and Aurorae

S. F. SINGER

Abstract—To explain the sudden commencement (SC) of magnetic storms, the reverse sudden commencement (SC*), and pre-SC disturbances, we invoke the following model: The solar eruption produces a shock wave which arrives at the Earth 22–34 hours later. High-velocity particles having a smaller interaction precede the shock wave and cause the pre-SC bay-like disturbances at high latitudes. The shock wave itself is retarded by the body forces produced by the geomagnetic field, but speeds up as it enters the auroral zones. In pushing out lines of force, it creates the polar SC* events. Charge separation in the shock wave produces the driving force for the SC currents, which flow in the atmosphere (in accordance with Vestine's analysis).

The storm decrease is produced by the high-velocity particles following the shock wave (up to nine hours later) which enter because of field perturbations into the normally inaccessible Störmer regions around the dipole. Here they are trapped and will drift, producing the ring current which gives rise to the storm decrease. Particles with a small pitch angle, however, can reach the Earth's atmosphere and contribute to aurora, the airglow, and ionospheric ionization. These particles are replenished by perturbations produced by solar influences having a 27-day recurrence. Many other particles are absorbed or scattered out of the trapping regions so that their number diminishes rapidly in a day or so, as does the magnetic-storm decrease.

The model thus attempts to explain for the first time the cause of the SC*, the atmospheric nature of SC, the delay between SC and the main phase, and the formation and decay of the ring current. A by-product is auroral-particle acceleration by a shockwave.

New experimental tests are suggested by the model: (a) Acoustic observations with balloons to look for the shock wave penetrating into the atmosphere in the auroral zones. (b) Observations with rockets or satellites to establish the location of the SC and main-phase currents. (c) Measurements of the nature and energy of the auroral particles.

INTRODUCTION

The purpose of this paper is to present a new model to explain some phenomena of magnetic storms and aurorae which are not adequately covered by existing theories. Our model at this stage certainly does not account for all the important phenomena. The basic philosophy of the paper is to develop ideas far enough to allow the planning of more suitable experiments both in the laboratory and in the field. The model serves to indicate certain crucial calculations which can be performed with some degree of confidence in that they correspond to the actual physical situation; these calculations are carried out in the appendices. The exact mathematical treatment of many of the phenomena is extremely complicated if not impossible and should perhaps be deferred until some of the crucial points have been settled by experiment or observation.

The paper is organized as follows: (1) a review of the phenomena of magnetic storms and aurorae (following closely the recent review by *Alfvén* [1955]); (2) a critical discussion of existing theories; (3) observational evidence on SC and SC*; (4) a model for the SC; (5) a model for the main phase of magnetic storms; and (6) a critical discussion of the model and of some crucial experiments relevant to it.

Note that the models for the SC and for the main phase are essentially independent of each other and are therefore discussed separately.

BACKGROUND

The first serious study of magnetic storms was made by Birkeland. Our present knowledge of the morphology of the magnetic storms is essentially due to Chapman and Vestine.

A magnetic storm often starts suddenly, and the time counted from the 'sudden commencement' is called the 'storm time.' If we take an average of many storms, starting at different times of the day, we obtain a characteristic curve which gives the storm-time variation D_{st}. For stations near the equator (or in any case far from the auroral zones) the storm-time variation has the shape shown in Figure 1. The magnetic field increases suddenly and remains higher than normal during a few hours. This is called the 'initial phase.' Then the 'main phase' begins, characterized by a strong decrease. The main phase slowly decays, and after two or three days the field returns to its initial value.

Main phase—The amplitude of the disturbance

during the main phase of a magnetic storm has two very pronounced maxima in the northern and the southern auroral zones, which are situated at about ±70° geomagnetic latitude. This part of the disturbance is often called the polar disturbance. There is a third maximum near the equator, referred to as the equatorial disturbance.

In order to study the cause of the magnetic storms, it is important to find the current system which produces the observed disturbance field. Unfortunately this cannot be done in an unarbitrary way unless we know the location of the currents.

Near the auroral zone, the magnetic-disturbance field varies very rapidly with the distance to the zone. This gives us good reason to assume that the polar disturbance is due to currents in the upper atmosphere. These currents flow along the auroral zone eastward in the evening and westward in the morning. On the other hand, it is usually supposed that the main phase equatorial disturbance derives from a ring current in the equatorial plane, flowing from east to west at a great distance from the Earth.

Chapman has constructed the current system under the assumption that all currents flow in the upper atmosphere. This current system is reproduced in most text books [for example, *Chapman* and *Bartels*, 1940, p. 310]. It is important to note that the only part of this current system that is likely to correspond to reality is the current system in the auroral zones. However, as the auroral currents are represented as flowing in circles around the poles, a very important property of these currents is lost, namely, that their polar distance varies in a systematic way with the time of day. This observation is of great importance in the theory of magnetic storms and aurorae proposed by *Alfvén* [1955].

Aurora—The aurora is observed in two zones at 20°–23° polar distance. For general description and classification see *Chapman-Bartels* [1940, p. 449].

According to Birkeland, Störmer, and Vegard the aurora is due to charged particles shot out from the Sun, which hit the upper atmosphere. According to Alfvén this view is very difficult to accept, because the relative motion of the Sun and the Earth would give rise to a very rapid systematic drift of the auroral patterns. No effect of this type has been observed.

A new theory has been proposed by *Bennett* and *Hulburt* [1954], in which it is assumed that the charged particles shot out from the Sun exercise a

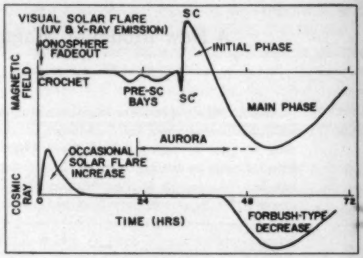

FIG. 1 – An idealized picture of a magnetic storm as a function of 'storm time'; SC, IP, and main phase are indicated; in addition, the picture shows two phenomena peculiar to the auroral zones: the pre-SC bays and the SC* which immediately precedes the SC

self-focussing effect so that the electrons are ejected and only a proton stream remains. It is argued that these protons, which have a velocity of the order of 10^{10} cm/sec, create a sufficient magnetic field so as not to follow a Störmer orbit; they are also affected by the magnetic field of the ring-current. The authors suggest that the protons may be incident in the auroral zone. One serious objection seems to be the fact that in order to account for the observed travel time, they require the protons to spend about 100 times the Sun-Earth traversal time in the vicinity of the Earth. Another difficulty pointed out by Ferraro is the possibility that the self-inductance effects are so large that the self-focussing stream may not have time to be set up between the Sun and the Earth. Both points deserve further investigation. Also, it is to be hoped that the difficult trajectory calculations for the beam will be carried out.

The other theories, proposed by Chapman, Ferraro and Martyn (see recent review by *Ferraro*, [1955] and by *Alfvén* [1955]) assume that the aurora is due to particles accelerated by local electric fields in the Earth's environment. Alfvén regards the aurora as a gaseous discharge in the upper atmosphere and in the space around the Earth. The electric currents of this discharge then are supposed to account for the magnetic disturbances. The aurora is an indication that concentrated currents flow in the upper atmosphere in the auroral zone. (These considerations all refer to the main phase.)

Alfvén also points to the diurnal variation of the polar distance of the aurora, which has a minimum in the morning. This variation is intimately connected with the diurnal variation of the polar dis-

tance of the currents producing the magnetic disturbance.

THEORIES OF MAGNETIC STORMS AND AURORAE

Chapman-Ferraro theory of sudden commencement—During the last few decades the Chapman-Ferraro theory of magnetic storms has dominated the discussion. Following a suggestion by Schuster, Chapman and Ferraro assumed that magnetic storms are caused by the emission from the Sun of a beam of ionized gas. As magnetic storms often occur one day after some event at the Sun, such as a solar flare or the meridian passage of a sunspot, the velocity v_0 of the beam should be such as to cover the distance from the Sun to the Earth in one day. This gives $v_0 = 2 \times 10^8$ cm/sec. Such beams have never been directly observed, but there is much indirect evidence for their existence.

The direct result of the theory is a qualitative statement that the arrival of an ionized gas cloud should produce an increase in the terrestrial field in the equatorial region. As in reality the field increases during the initial phase but decreases during the main phase, they identify this phenomenon with the initial phase.

The C-F theory can be criticized on several grounds. *Alfvén* [1955] has pointed out that the assumption of zero magnetic field inside the beam is artificial. It implies that the beam is produced in a region of the Sun where the magnetic field is zero. Further, as a result of this assumption the gas of the beam is stopped at a large distance from the Earth. (In our opinion the gas from the Sun may well be ejected from a region where the field is very low so that the field in the beam plays a minor role in the development of the magnetic storm. As we shall see, the penetration of the Earth's field can be achieved in the auroral zones.)

In the C-F theory the beam is represented as a cloud of gas having a sharply defined, infinite front surface which proceeds into the Earth's field. *Gold* [1955, p. 103] has pointed out that the existence of such a sharp front and hence the production of a sharp increase in the magnetic field can only be understood in terms of a shock wave, since otherwise the collimation of particle velocities would have to be extremely good.

There are other and more serious objections. The C-F theory does not explain the reverse sudden commencement SC* or the pre-SC disturbances (see below, under *Observational evidence* on SC and SC*, items (d) and (e)).

Most serious is the fact that the C-F theory neglects the presence of ionized gas between the face of the solar stream and the surface of the Earth. The integrated conductivity is very large, many times the value of the ionospheric conductivity (see Appendix 2). Hence it is not possible for the magnetic field increase, which occurs when the beam surface is retarded by the Earth's field, to propagate without great attenuation and without changing its rise time. It does not seem possible to produce the observed rapid increase of magnetic field at sea level by any process, however sharp. As we shall see later, we are forced to the conclusion, suggested and substantiated by experimental evidence, that the currents responsible for the sudden commencement flow in the Earth's atmosphere.

C-F theory of main phase—In order to explain the decrease of the equatorial field during the main phase, Birkeland and Störmer supposed that there is a ring current in the equatorial plane at a few times the Earth's radius. This conception has been included in Chapman-Ferraro's theory. Without any detailed arguments, it is assumed that when the ionized cloud is stopped at some distance from the Earth, charged particles are emitted in such a way that they move in circles around the Earth, thus producing a ring current.

The stability of this ring current has been questioned by *Alfvén* [1955] since in the dipole field of the Earth, a circular orbit is certainly not stable. (This holds for a single particle; it very likely also holds for a multitude of particles.)

On the other hand Alfvén's picture of the ring current is based on a trochoidal motion of electrons which is certainly stable. Our model also employs particles drifting in a trochoidal motion but differs from Alfvén in the manner in which the current is set up and in the types of particles which are responsible for it.

Starting from the Chapman-Ferraro picture of a ring current, *Martyn* [1951] has developed a theory of the aurora; he uses the Hall polarization across the current to accelerate auroral protons. The C-F-M theory also speaks of the electro-magnetic inertia of the current to account for its stability and for its persistence. However, no calculation of this stability is presented for the growing and decaying current.

Aside from the question of stability of the ring current, its manner of formation is of some importance. The C-F-M theory assumes that protons having a radius of curvature larger than the hollow that is formed around the Earth by the stream start the current by pulling electrons after them. It is not quite clear why this should be so, since the electrostatic forces occur only if there are

space charges present. The ions and electrons then are supposed to drift together in circles, with the ions moving at a slightly higher velocity so as to obtain a current. Again, it is not quite certain why the ions should have a higher velocity or why indeed a current of the required magnitude should occur.

Alfvén's theory—Alfvén [1955] has put forth an 'electric field theory' of magnetic storms and aurorae. This theory accepts the Schuster-Chapman-Ferraro arguments for the existence of a beam of ionized gas as the cause of magnetic storms. However, contrary to their theory it assumes that the magnetic field inside the beam is not zero. This implies that owing to the motion, the beam becomes electrically polarized. The electric field of the beam is considered to be the most important property of the beam. Alfvén calculates the motion of electrons in the combined electric field and magnetic dipole field. This leads first to a counter-clockwise (as viewed from the north pole) current (which he identifies with SC), later to a clockwise current (which he identifies with the main phase).

Several objections can be raised to Alfvén's theory. Like the C-F theory, it places the SC currents at large distances from the Earth. This seems to be contrary to the experimental evidence (see below *Observational evidence* on SC and SC*, item (c)). The electric field is visualized by Alfvén as the obvious cause of a current system. Even though the field may exist (and explain, for example, the diurnal variation of aurora) we do not consider this as a necessary condition to explain the main phase of magnetic storms. (We believe the sudden commencement currents are produced by an electric field within the atmosphere; but this field is quite different from the one envisaged by Alfvén.)

An important question that has not been answered by either the C-F-M theory or Alfvén's is concerned with the time constant of the magnetic storm: the delay (typically eight hours) between the sudden commencement and the maximum of the main phase, and the decay time (typically two days) of the main phase. Our model tries to account for these times in a natural way.

Observational Evidence on SC and SC*

We now list some observations which are relevant to the theoretical model to be discussed under the next two headings of this paper.

(a) *Newton* [1944] has derived a time lag of 22 hours for great magnetic storms (and 34 for storms of smaller intensity) between the central meridian passage of active sunspots and the commencement of a great storm.

(b) A world-wide SC is observed; it consists of a rise in the magnetic field within a short time interval (of the order of a few minutes).

(c) The SC varies considerably from place to place. A careful statistical analysis by *Forbush* and *Vestine* [1955] has established that the SC (and the initial phase, IP) are enhanced during the daylight hours at Huancayo, thus indicating an atmospheric source for SC and IP (see Fig. 2). These suggestions had been made previously by *Vestine* [1954] and *Sugiura* [1953]. Even earlier, *Chree* [1912] had given evidence that the SC's are larger in the auroral regions than elsewhere (by perhaps a factor of 4), and *Fukushima* [1951], in analyzing the storm of August 4, 1949, concluded that SC is enhanced in the auroral zone and on the daylight side. Measurements with induction magnetometers also show a daytime enhancement of SC [*Kato* and *Utashiro* 1950].

(d) In his discussion of the diurnal variation of SC, *Newton* [1948] points to the occurrence of SC*, a reverse impulse in the horizontal force component which often precedes the SC increase by about a minute or so. A careful study of the distribution of SC* with respect to local time and latitude has been made by *Nagata* and *Abe* [1955] who conclude that it can be represented by a high-latitude upper-atmosphere current system consisting of a strong clockwise vortex at about 14h, and a weaker counterclockwise vortex centered at 06h (see Fig. 3).

(e) *Fukushima* [1951] has called attention to a pre-SC bay-like disturbance at high latitudes. It preceded the onset of the magnetic storm by about one hour. During the magnetic storm, disturbances were observed which take place intermittently along the auroral zone [*Fukushima*, 1952]; these were attributed to occasional concentrations of corpuscular radiation.

(f) A phenomenon possibly related to (e) has been discussed by *Heppner* [1954] who related high-latitude bay disturbances to changes in the appearance of the aurora.

New Model of Sudden Commencement

In order to account for the observational data of the sudden commencement we have developed the following physical picture.

We first adopt the point of view that we are dealing here with an interplanetary shock wave. This suggestion was advanced by *Gold* [1955, p. 103] to explain the high degree of collimation in

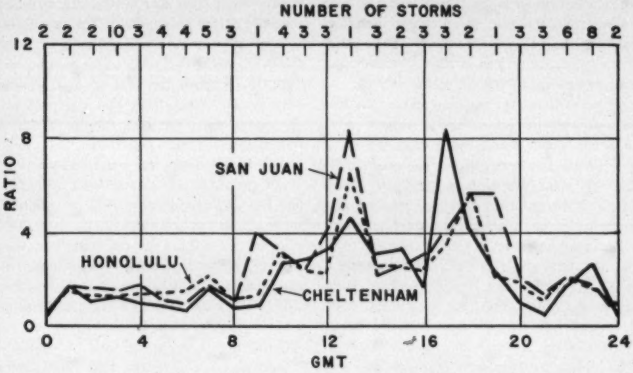

FIG. 2 – The ratio of mean hourly value of the initial phase of the magnetic storm at Huancayo, Peru, to that at stations indicated (corrected for S_q); this graph clearly shows the enhancement of the initial phase at the equator as compared to other latitudes and has been ascribed by Vestine to the increased conductivity of the ionosphere at the equator.

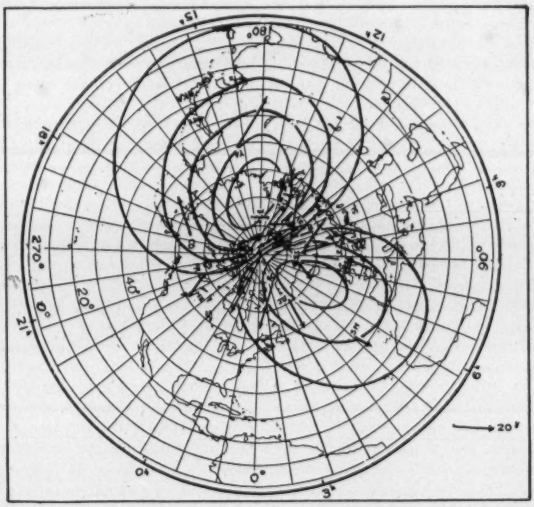

FIG. 3 – Distribution of the equivalent current system of the reverse impulse of SC*; the current arrows are shown for the different stations where observations were made, drawn for 06h 25m UT on May 29, 1933 by *Nagata* and *Abe* [1955]

time of the world-wide SC, even after a long travel time from the Sun (see previous headings (a) and (b)). This of course accounts for the sharp face of the approaching gas in the C-F theory but does not yet explain the origin of the SC.

We will now discuss the physical picture further. Since a high-velocity jet of gas is emitted from the Sun, there is little doubt that a shock wave will develop. We do not here discuss the mechanism whereby the solar eruption is produced. Such questions and the question of its propagation into the corona and possible effects of a solar magnetic field and sunspot fields are, of course, common to all theories attempting to account for magnetic storms. We accept the fact that a magnetic storm is observed as an indication that the gas has been ejected. In Appendix 1 we estimate the disturbance velocity to be about 50 times the velocity of sound in the interplanetary medium between Sun and Earth. The mean free path in this medium we estimate to be of the order of 10^{-2} that of the Sun-Earth distance. It seems therefore necessary to find arguments why a shock wave should *not* develop.

An interesting consequence of the picture can now be developed: From the theory of strong shocks we deduce also the velocity to which the gas behind the shock wave is accelerated, namely $\frac{1}{4}$ of the shock velocity. This leads to the result that the solar gas arrives in the vicinity of the Earth about seven to ten hours after the shock itself, that is, just about at the beginning of the main phase. (Of course, the original interplanetary gas arrives soon after the shock wave; thus the main-phase current builds up at large distances from the Earth while the IP currents flow in the atmosphere.) We might identify the SC with the shock wave and the maximum of the main phase with the arrival of the corpuscular stream.

We now consider what happens when the shock wave impinges on the Earth's dipole field. The gas enveloped by the shock, likewise therefore the field B in the equatorial plane, is compressed. Since the conductivity is very high, the increase in B cannot be felt ahead of the shock wave immediately (that is, with the velocity of light). Instead we must consider the magnetohydrodynamic situation: The question then is whether the shock wave (and hence ΔB) do propagate to sea level or even to the ionosphere. The gas behind the shock has now been set in motion perpendicular to B_0, and it experiences therefore a body force and a retardation. The resulting expansion waves will catch up with the shock and stop it. This process should occur some Earth radii out, well above the ionosphere (see Appendix 2). This process of course is equivalent to the retardation and stopping of the beam in the C-F model. It is seen however that with the ionized medium of high conductivity between the shock front and sea level, and with the strong magnetic field, the disturbance cannot propagate with finite amplitude.

Above and below the equatorial plane the field is not perpendicular to the shock velocity; therefore less or no retardation will be experienced by the shock. It appears therefore that the shock front will curve. Applying this reasoning in a continuous manner, we find that the shock should enter the northern and southern auroral zones (see Fig. 4).

We now view the shock wave as it propagates into the auroral zone. It will be bent by the magnetic field, and we can consider the magnetic lines of force as a kind of elastic wall which confines the shock wave, like the walls of a shock tube. Now it is well known that a converging shock wave increases in strength as some power of the area. From theory and laboratory data we have estimated the increase in strength of the shock wave to be about five. The velocity of the shock front therefore would be increased from 2×10^8 cm/sec to $\sim 10^9$ cm/sec, in other words high enough to produce auroral effects, ionization, and motions of the auroral ionosphere. The details of the calculation are given in Appendix 3.

We must remember, however, that the walls that confine the shock wave are not perfectly rigid but can be pictured as elastic lines of force, exerting a magnetic pressure to counterbalance the dynamic pressure of the shock wave. Therefore the walls will 'give' when a shock wave becomes strong. This in effect pushes out lines of force and produces an event which we identify with the SC* event, namely a decrease of the field preceding the shock wave's arrival and preceding the sudden-commencement increase.

An examination of the experimental data on SC* (see Fig. 3) would indicate that the shock wave is also twisted in longitude. One would expect also that because of the gradient of the magnetic field, a charge separation should take place. (Compare later discussion on the motion of individual particles.) This cannot be easily calculated; for the present we postulate this charge separation in order to explain the production of an EMF which drives the SC currents in the lower ionosphere (in accordance with the evidence given (item (d) above). In the higher ionosphere, the electric field should be strong enough in the auroral zone to

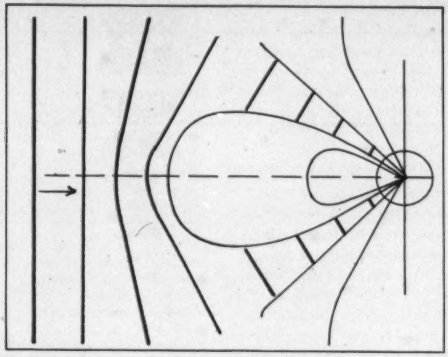

FIG. 4 – Position of the shock front in the Earth's dipole field at successive intervals; the shock advances from left to right, is stopped in the vicinity of the equator but can advance into the auroral zones where the field does not oppose its motion

FIG. 5 – Average current system of the disturbed field for sudden commencements; the centers of the vortices are located at 15h and 09h; from *Jacobs* and *Obayashi* [1956]; note the similarity to Fig. 3

accelerate ions and electrons, causing a considerable amount of auroral excitation. When the collision frequency becomes high enough (in the lower ionosphere), a current is set up. This process is discussed in greater detail in Appendix 3.

Further evidence for this peculiar behavior of the high-speed gas in the auroral zone, its rotation in longitude and its confinement in a tube of magnetic force, is shown in a recent analysis by *Jacobs* and *Obayashi* [1956]. Their picture reproduced as Figure 5 shows two vortices very similar to those of the SC* but in the opposite sense, hence interpretable as the collapse of lines of force and increase of magnetic field after the pressure of the high velocity gas has been removed.

Finally, another mechanism must be explored, namely the suggestion by Nagata that the incidence of the high-velocity particles and the resulting production of ionization enhances the conductivity so much as to produce the SC currents with existing EMF's. We think it likely that this mechanism can act as a contributing factor.

The question of the progress of the shock wave in the Earth's atmosphere can now be discussed. The velocity of the gas is high enough so that dissipation by ionization and luminosity is quite important. The atmospheric density increases exponentially. One would therefore expect the shock wave to be both attenuated and reflected, degenerating into a sound wave in the atmosphere (see Appendix 3). It may be possible to detect such a sound wave with ordinary acoustic means, for example, by a microphone, carried in a high-altitude balloon. An observation of this type, coupled with simultaneous observations of the sudden-commencement increase at sea level, would support the magnetic-storm model suggested here.

Pre-SC bays—It is finally necessary to account for the fact that magnetic disturbances are observed at high latitudes before the sudden commencement (see item (e) above). This can be explained by the emission of high-velocity particles during solar eruptions such as have been observed by radio methods. These high-velocity particles

by virtue of their much smaller interaction and cross section can arrive ahead of the shock wave. (This is clearly the case for cosmic-ray particles which lose only very little energy in driving the shock wave. To a lesser degree, the same argument can be applied to auroral particles, most likely protons having energies of several Mev.)

Model of Main Phase of Magnetic Storm

In common with other theories, this model regards the main phase of the magnetic storm as produced by a current encircling the Earth, flowing from east to west. However, in contradistinction to the C-F-M theory and to Alfvén's, the current is found distributed at various distances from the Earth, and is carried by spiraling protons and electrons drifting in opposite directions. These particles are not confined to the equatorial plane but enclose the whole space around the earth.

The origin of the particles is in the high-velocity gas following the shock wave. First, particles arrive which have been accelerated in the vicinity of the Earth by the shock wave, later followed by the gas which has been pushed out from the Sun itself.

In accordance with Störmer's theory, a single low-energy particle could not approach the vicinity of the Earth but would be deflected away by the Earth's dipole field. However, if a particle were transferred by some means close to the Earth, it would stay attached to a line of force and spiral around it. The problem therefore is to transfer the particles from say 20 to 40 Earth radii out into the inner allowed region. For higher-energy particles, this is possible when the Störmer impact parameter γ is greater than -1 (see Fig. 6); then the particles can fill up the inner region but will disappear again once the supply of particles outside the Earth is gone. Consider now, however, (1) that particles once in the inner region are scattered or (2) that the magnetic field deviates from a dipole. (Mechanism (1) for placing particles into a trapped region was proposed some time ago by *Alfvén* [1947] in connection with explaining the absence of a diurnal variation of cosmic rays in the presence of a supposed solar dipole field. This was applied by *Kane*, *Shanley*, and *Wheeler* [1949] who studied in detail the scattering of low-energy cosmic-ray particles by the Earth's field from allowed into trapped orbits of the solar dipole and calculated the filling up of trapped orbits.) This will change the pitch angle with respect to the magnetic field, and likewise the impact parameter γ. If γ decreases and becomes less than -1, then the particles are trapped in the inner region and can no longer

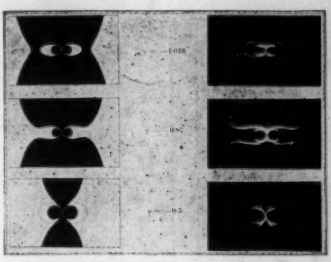

Fig. 6 – Diagram showing the allowed and forbidden spaces in the vicinity of the Earth's dipole according to Störmer; (γ respectively -1.016, -0.97, and -0.5 from top to bottom) it is seen that small changes of γ near $\gamma = -1$ can open up or close to infinity the allowed region in the immediate vicinity of the dipole; this region extends narrow funnels into the Earth's atmosphere in the auroral zones; for particles of very low energies, encountered in solar corpuscular streams, the simpler perturbation methods of Alfvén can be used to discuss the problem of trapping in the Earth's dipole field

escape. For the low-energy particles present in the solar stream, we can use much simpler methods based essentially on the perturbation techniques developed by *Alfvén* [1950, pp. 13–34]. It is necessary to make only the very reasonable assumption that during the approach of the stream, the Earth's field is modified so that it is no longer a dipole field. Particles therefore will leak into the inner region and attach themselves to a line of force. During the time the field is disturbed, the intensity of particles in the trapped region should approach the particle intensity on the outside, although perfect equilibrium may not be established. After the disturbance is over, the outside density of particles becomes very small, but the leakage of particles out of the Earth's field is very much reduced also.

We have therefore a model in which, after the passage of the shock front and after the passage of the gas cloud across the Earth's orbit, the Earth is left with a large number of particles trapped in its magnetic field. That this actually occurs is suggested by the very old pictures of Birkeland (see Fig. 7) which show a luminous region near the Earth due to such trapped particles. This has been evidenced also by the beautiful experiments of *Bennett* [1956] using the 'Störmertron.' (We do not however agree with Bennett's view that the particles are trapped when they lose energy in approaching the Earth's atmosphere. This would not change their pitch angle and therefore would not affect γ. The important process in our opinion

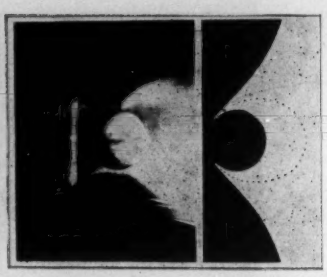

FIG. 7 – Electron concentration in the vicinity of Birkeland's terrella; the electrons are incident from the right; note especially the crescent-shaped luminous region away from the direction of incidence of electrons; it indicates the presence of electrons in trapped orbits, probably scattered there in collisions with the residual gas in the chamber; this figure is taken from *Störmer* [1955]

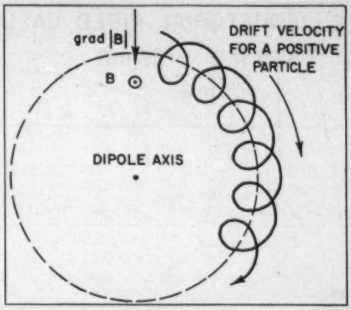

FIG. 9 – The motion of a charged particle in the Earth's equatorial plane; the drift motion is due to the combined effects of the magnetic field and the field gradient; the sense of the drift velocity is shown for a positive particle; a negative particle would drift in the opposite direction

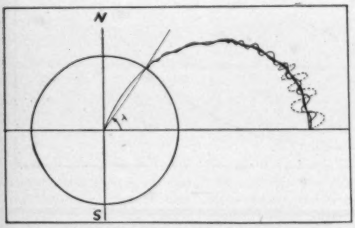

FIG. 8 – Diagram showing the motion of low-rigidity particles tied to a line of force; particles starting out with a large pitch angle are soon reflected (dashed line); only particles starting with a very small pitch angle (solid line) can reach the Earth's atmosphere

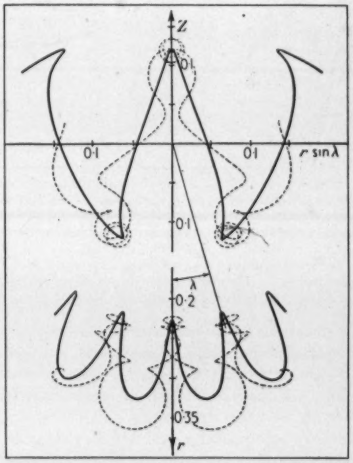

FIG. 10 – Motion in a dipole field calculated by Störmer and by Alfvén's perturbation method; upper drawing shows projection on a plane through the axis of a dipole; lower drawing upon the equatorial plane; the drift of a positive particle is again from east to west and is seen to occur mostly when the particle is near the equatorial plane

takes place at large distances from the Earth, near the equatorial plane.)

We now investigate the subsequent behavior of the trapped particle cloud in the vicinity of the Earth. Starting with a pitch angle α_0 in the equatorial plane, where the field is B_0, a particle will spiral along a line of force towards either the north or the south until the field strength increases to $B = B_0/\sin^2\alpha_0$; there the pitch angle increases to 90°. There the particle will be reflected (see Fig. 8) through the equatorial plane into the other hemisphere, and continue this motion until other effects become important. Simultaneously, because of the gradient of the magnetic field, the particles will drift in azimuth, the protons to the west the electrons toward the east, thus setting up a westward electric current. This current we identify with the Störmer ring current.

We now calculate this current as follows: *Alfvén* [1950, pp. 27–34] has worked out a method

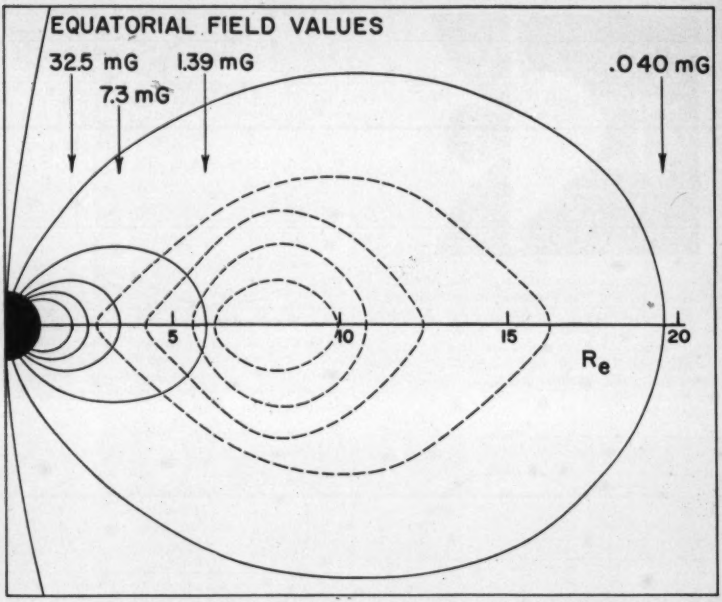

FIG. 11 – The distribution of the main-phase ring current in the vicinity of the Earth; the dotted lines connect points of equal current density; the region between the lines as well as the central region enclose a total current of 1,000,000 amp; the calculations were made for a particle density in the equatorial plane of one per cm³; beyond about eight Earth radii, the current is limited by the field gradient, and self-reaction must be included in a more precise treatment; up to $R_e = 8$ Earth radii, the current is determined by the particle density and could be raised if the particle density is raised (examination of Figure 14 shows that a particle density of 10 per cm³ would shift the current density maximum to six Earth radii); the current shown in this graph has a total value of about 4×10^8 amp, about twice as much as is needed to account for a very strong magnetic storm

for calculating the advance in azimuth of a particle spiraling in the Earth's magnetic field. Particles whose α_0 is 90°, that is, confined to the equatorial plane, will undergo a simple trochoidal motion (see Fig. 9). These particles will drift the fastest. Particles with smaller α_0 will spend considerable time away from the equatorial plane where the drift is extremely small (see Fig. 10). It is necessary therefore to calculate the time taken for an oscillation. The details are shown in Appendix 4. It becomes thus possible to calculate the average azimuth drift velocity per particle as a function of pitch angle α_0, equatorial distance from the center of the Earth R_e, and velocity V_0. From these results we can calculate the current and its distribution in the space near the Earth (see Fig. 11).

A small density of particles (~1/cc) suffices to provide the current necessary to produce the main phase of the magnetic storm.

Stability—We now investigate the stability of the current. The range of a proton with velocity 2×10^8 cm/sec is 10^{-4} g/cm². Hence, it has a lifetime in the space around the Earth of 10^3 days. The chief method by which particles disappear is through absorption in the Earth's atmosphere. However, because of the reflection when the pitch angle reaches 90°, the trapping for the particles is very effective. Only particles having a pitch angle less than ~2° can escape into the atmosphere. As a result, the pitch-angle distribution will exhibit a 'hole' around zero pitch angle after about 30 seconds. This empty region is then continuously fed by particles which are scattered in various ways, either by field changes or by atomic collisions, so that there is a continual leakage of

particles with large pitch angle into the nearly empty small-pitch-angle region, and therefore into the atmosphere. We can estimate the lifetime of the ring current as follows: Since the empty pitch-angle region occupies about 0.0005 of the solid angle, the lifetime (neglecting leakage into space) is of the order of 30×2000 sec, or about one day. This time is in good accord with the experimentally observed decay of the main phase of magnetic storms.

Distribution of ring current—Our model leads to a particular distribution of the ring current. Because of the magnetic reflection most of the particles are confined to $\pm 15°$ of latitude. In any case beyond $\pm 30°$ we would expect little drift velocity, and therefore little current. At small distances from the Earth, the current is limited by the small number of particles and by the low drift velocity; at large distances the current is limited by the effects of its own magnetic field. Details are given in Appendix 4 (see also Fig. 11).

Conclusions—We conclude that the main-phase currents build up immediately following the SC and that their magnetic effects are superimposed on those of the atmospheric SC currents during the initial phase. Several hours after the SC only the main phase currents remain.

Our model for the ring current also serves to make plausible the 27-day recurrence features of storms and aurorae. Weak solar beams (that is, those having low density or low velocity) will perturb the Earth's field very far out, whereupon particles will be captured and will produce the ring current in the manner described in Appendix 4.

Critical Discussion of the Present Model and Suggested Experiments

The crucial points of the model presented here need to be verified, preferably by observations of new phenomena, but also by laboratory experiments or more elaborate calculations.

The bending of the shock front—This point could be checked by laboratory experiments. In collaboration with E. L. Resler we have proposed an experiment in which a shock wave of Mach number 15 produced in a shock tube is allowed to interact with an inhomogeneous magnetic field. From an examination of the scaling factors, it appears that this experiment could simulate the interplanetary shock wave interacting with the Earth's magnetic field. An outline of the proposed experiment is presented in Appendix 2.

Increase in strength of the converging shock wave in the auroral channel—A measurement of the velocity of the gas in the channel would provide a good check of the correctness of the calculations. Rocket measurements of the particles and particle energies would therefore be desirable. Another approach would be to look for the acoustic wave which remains after the shock wave has been attenuated by the dense atmosphere. A balloon carrying a microbarometer, launched several hours after a solar flare in the auroral zone, would stand a good chance of picking up this effect if indeed it does exist. From the measured strength of the sound wave it should be possible to calculate the properties of the shock wave incident on the Earth's atmosphere.

Driving EMF for the SC currents—It is extremely difficult to calculate how the incident shock wave actually sets up the SC currents in the ionosphere. Calculations on a somewhat simpler model may make the picture more plausible.

It would be important also to observe the ionosphere during a sudden commencement, to observe both the increase in ionization which may be expected and the possible motion of the ionospheric gas due to the impact of the shock wave. A preliminary calculation of this effect has been made by J. M. Burgers.

Aurora—In common with other theories, there is the problem here of explaining the high energy, and therefore velocity, of the particles directly responsible for the aurora, as against the low velocity of the particles traveling from the Sun. It is possible that low-altitude aurorae are in many cases produced in the acceleration effect of a shock wave, as was discussed in connection with the sudden commencement. This would imply that small shocks occur at various times, which are adequate to produce auroral displays but do not set off appreciable magnetic storms. It may be possible to observe the acoustic effects of these shock waves within the lower atmosphere. It would be desirable also to measure the radiation directly responsible for the aurora *in situ* by means of rockets.

SC currents—An important point of our model as opposed to the Chapman-Ferraro-Martyn theory and the Alfvén theory is the fact that the SC currents flow in the atmosphere. This point could be easily checked by means of a magnetometer located just above the ionosphere. The measurement is best made at the equator. The magnetometer could be carried by a rocket (provided it were launched at the right time) or by an artificial satellite [*Singer* 1954, p. 370; 1956, p. 215] (Fig. 12). The latter would provide continuous

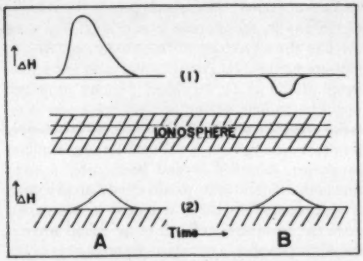

FIG. 12 – Proposed rocket or satellite experiment to differentiate between currents flowing beyond the ionosphere (Case A) and currents within the ionosphere (Case B); while the sea-level magnetometer (2) will indicate the same in both cases, the satellite magnetometer will show quite a different behavior according to whether the current flows above it (Case A) or below it (Case B)

coverage in time and would allow measurement of the latitude distribution of the current flow.

Main phase 'ring' current—The same experiment using a magnetometer in a rocket or satellite would establish the location of the main-phase currents; there seems to be little doubt, however, that they are located above the ionosphere, at least outside of the auroral region. Of greater interest in this connection would be a measurement with an extremely high-altitude vehicle capable of traveling to an altitude of several earth diameters to verify the distribution of the current (Fig. 11) and determine the nature and energy of the particles making up the current.

Acknowledgments—My interest in magnetic storms was aroused by some stimulating and controversial lectures given at the University of Maryland by E. H. Vestine and H. Alfvén during the spring of 1954. I owe to the latter my conviction that scaled laboratory experiments can furnish a valuable guide for interpreting the nature of cosmic phenomena. It is a pleasure to acknowledge many useful discussions on shock waves and magnetohydrodynamic problems with my colleagues J. M. Burgers, S. Pai, and E. L. Resler. I am indebted to Resler also for his collaboration in the planning of the laboratory experiments to test some features of the present model. R. C. Wentworth assisted in many of the computations. R. Rhodes considered some features of the motion of particles in a dipole field in his master's thesis (June 1955).

The portion of the work dealing with trapped particles was reported at the IUPAP Cosmic Ray Congress, Guanajuato, Mexico in September 1955. Assisted by the AF Office of Scientific Research under Contract AF18(600)-1038.

Note added in proof (Mar. 11, 1957)—Four substantial arguments have been raised concerning the theory of magnetic storms proposed by the author. These arguments and the replies are discussed below:

(1) It is argued from the fact that λ is very much greater than R_E that Gold's suggestion by itself does not make the Chapman-Ferraro model workable. The passage of the shock front would be too slow to produce the SC. This situation is remedied however when we consider the shock in the atmosphere where λ is small.

(2) *Momentum balance*—Spitzer and others have pointed out that the incoming shock wave carries a considerable amount of momentum which is taken up by the magnetic field and should give rise to a sudden commencement increase at the equator. We believe that it is not possible for a finite amplitude wave to be transmitted perpendicular to a strong magnetic field in an ionized gas. (The treatment which shows the reflection of the shock wave is identical with this statement.) Rather the momentum is transmitted along the lines of force since there the wave can travel at a much higher velocity.

(3) *Dynamic stability of the ring current*—It has been argued by Schülter that the gravitational and centrifugal forces must be brought into a discussion of the stability of the ring current. This point is appropriate for the discussion of the Chapman-Ferraro current (which is imagined to operate in a vacuum) but hardly applies to our case. The inward electrodynamic force $\mathbf{I} \times \mathbf{B}$ is $\sim 10^8$ dynes, giving an inward pressure of about 10^{-12} dynes/cm^2. However, this figure is only a minute fraction of the ambient gas pressure nkT of 10^{-9} dynes/cm^2, so that equilibrium can easily be achieved.

(4) Local difference in the main phase variations: Gold has brought out that individual storms show large differences, e.g. along the equator. (These differences are removed in the averaging of storm data.) In our opinion this observation does not contradict the existence of an extraterrestrial ring current but merely shows that an atmospheric current coexists. As remarked in our paper, this superposition generally happens during the initial phase when the SC (atmospheric) currents are still quite strong.

Appendix 1—Physical Parameters of Interplanetary (IP) Shock Waves

We start by establishing first some basic facts. The disturbance causing an SC propagates to the Earth in some 20 hours, hence with a velocity of about 2×10^8 cm/sec.

If we assume the IP matter at rest before the disturbance reaches it, we have the typical condition for the establishment of a shock wave, since the disturbance velocity is supersonic; we estimate the velocity of an Alfvén wave as

$$H\left(\frac{\mu}{4\pi\rho}\right)^{1/2} \sim 10^{-4}\left(\frac{1}{4\pi \times 1.6 \cdot 10^{-22}}\right)^{1/2}$$

$$= 4 \times 10^8 \text{ cm/sec}$$

We can now compute the Mach number and therefore the strength of the shock as about 50, a very strong shock indeed.

Next we investigate whether the mean free path λ is

small enough to allow a shock front to be formed between the Sun and the Earth; the width of the shock front can be taken as three to four times λ; $\lambda = 1/nS$; if we assume a very high degree of ionization to exist, then S is determined by the Coulomb interaction between ions and electrons [*Alfvén*, 1950, p. 55]

$$S = (2.4 \times 10^{-5}) \frac{Z^2}{T_e^2} \text{cm}^2$$

We will take $Z = 1$, and assume $\log T_e$ in IP space ~4–5; then $S = 2.4 \times 10^{-13}$ to 2.4×10^{-15}.

Probably the best value near the Earth is 10^{-14} cm²; then with $n_e \sim 10^8$/cc, $\lambda_e = 10^{11}$ cm and the width of the shock front is about 3 to 4×10^{11} cm compared to a Sun-Earth distance of 1.5×10^{13} cm. It may also be compared with the Earth's radius of 6.4×10^8 cm. In the Earth's upper atmosphere, of course, the shock front is very much thinner.

Appendix 2—Behavior of Interplanetary Shock Wave in the Earth's Dipole Field

The conductivity in the region in which the shock wave interacts with the Earth's magnetic field is given by $\sigma = 1.4 \times 10^7 T_e^{\frac{1}{2}}/Z$. Numerically it is ~$2 \times 10^{13}$ esu. (Copper has a conductivity of 5×10^{17} esu.)

We can calculate a magnetic Reynolds number

$$\mathbf{R}_m = \frac{4\pi}{c^2} \sigma v l \sim \frac{4\pi}{c^2} 2 \times 10^{13} \times (2 \times 10^8) \times 10^9$$

which is clearly much greater than unity. It is therefore permissible to obtain an estimate of the situation by comparing the gas kinetic pressure ρv^2 with the magnetic pressure $B^2/8\pi$. If we take the particle density in the stream as n, then

$$n(1.6 \times 10^{-24} \text{ gm})(2 \times 10^8 \text{ cm/sec})^2 = B^2/8\pi$$

For $n = 10^3$/cm³, we find B to be about 4×10^{-2} gauss, which corresponds to a distance R_e of two Earth radii. Hence the shock wave will compress the field up to this distance, will be retarded and will finally stop.

It is seen that this result is in no way different from and adds nothing to the Chapman-Ferraro theory. The shock wave only accounts for the sharp face of the beam.

The important questions to settle are: (1) What is the effect of the field compression at sea level. (2) What is the behavior of the shock wave above and below the equatorial plane.

With regard to (1), the simplest way to discuss this problem from a physical point of view is to consider first the situation when a vacuum exists between R_e and sea level. Then the compression of the field ΔB is transmitted to sea level with the speed of light. But since in actual fact the space has nearly infinite conductivity, propagation of ΔB means also a propagation of $\Delta\rho$. But this violates our earlier conclusion that the shock wave has been stopped. One point which deserves further investigation is the propagation of an infinitesimal magnetohydrodynamic wave.

With regard to (2) since the three-dimensional calculation of the interaction of the shock wave is difficult, we have designed in collaboration with E. L. Resler the following model experiment to be carried out in a shock tube. We wish to reproduce in the laboratory some of the conditions which are believed to occur when a shock wave produced by solar corpuscular emission impinges on the Earth's magnetic field. We are particularly interested in observing the shock front to detect a possible curvature produced by the differential propagation velocity.

In order to simulate the actual conditions as closely as possible, we must apply suitable scaling factors. The distance involved is about two Earth radii (in

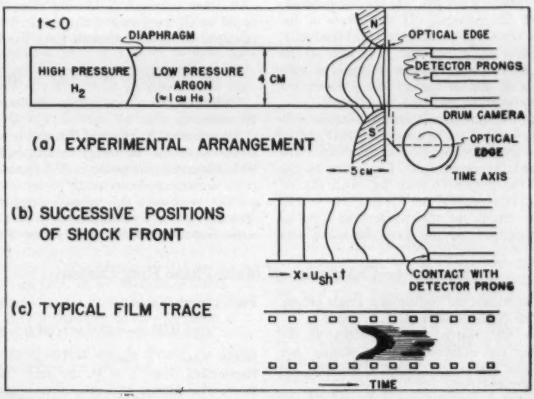

FIG. 13 - Proposed shock tube experiment to simulate the incidence of an interplanetary shock wave on the Earth's magnetic field

the equatorial plane), that is, 2×10^9 cm. Our laboratory dimension is about 2 cm, giving a scaling factor of 10^9 which must be applied to B, σ, and n_e. In the actual case, B varies from 10^{-4} gauss to 0.5 gauss, n_e from 10^2 up to 10^6. We will leave σ out of consideration for the time being, since the gas will be highly ionized (about 50 pct). We should therefore produce fields of at least 10^5 gauss and n_e of 10^{11}–10^{14}/cc.

An incident strong shock wave itself can produce an electron density of 10^{16} or 10^{17}/cm³; therefore, with a Mach number of 10 we can achieve a conductivity of one mho/cm [*Atkinson* and *Halden*, 1954; *Lin*, *Resler* and *Kantrowitz*, 1955]. If it seems desirable, the conductivity could be increased by a factor of ten by raising the Mach number to 15; but this requires a somewhat more elaborate instrumentation.

We can now construct a nonhomogeneous field of about 10^4 gauss to simulate the Earth's dipole field (see Fig. 13), and calculate roughly the distortion of the shock front: The gas behind the shock has a velocity of about 3 km/sec; then

$$\sigma(v \times H) = \frac{10 \text{ mhos/cm } (3 \times 10^5 \times 10^4)}{10^8} = 300 \text{ amp}$$

and the deceleration is

$$\frac{i \times H}{\rho} = \frac{\frac{300}{10} \times 10^4}{0.0001} = 3 \times 10^9 \text{ cm/sec}^2$$

$$s = \tfrac{1}{2} at^2 = 0.6 \text{ cm}$$

We estimate that with a field of 10000 gauss or more we could produce a measurable distortion of the shock front. We estimate that the edge can be lined up to 0.1 mm; the film in the drum camera is spinning about a vertical axis at 200 m/sec. We can resolve about 80 lines/mm. Therefore we can resolve time to $1/200 \times 10^3 \times 80 = 6 \times 10^{-8}$ sec. Our space resolution is the distance the shock wave travels in this time, or

$4 \times 10^5 \times 6 \times 10^{-8} = 0.024$ cm, about $\frac{1}{10}$ of the estimated effect.

Appendix 3—The Behavior of the Shock Wave in the Auroral Zone

The simplest method in the laboratory for achieving a converging shock is by the use of a shock tube with a converging channel. This, however, results in the hottest region of the gas being in close thermal contact with the cold walls. *Perry* and *Kantrowitz* [1951] have designed an axially symmetric shock tube in which the region of convergence is comparatively well isolated thermally from the walls. Their theoretical treatment based on a method by *Guderley* [1942] indicates that the strength of a strong converging shock varies inversely with a power of about 0.4 (for $\gamma = 1.4$) of the surface area of the wave, thus becoming very great close to the center of convergence.

To apply the theory to the problem of the propagation of the shock into the auroral region involves a considerable extrapolation. We ought to take due account of the following features: (1) the three-dimensional nature of the problem; (2) the effects of the curvature of the lines of force (magnetic field gradient); (3) the non-rigidity of the magnetic walls; and (4) the fact that the shock thickness now occupies a substantial fraction of the space since the cross-section for high-velocity particles becomes quite small.

Nevertheless, we can make some reasonable estimates: Point (2) leads us to the conclusion that charge separation plays an important effect as the shock wave progresses toward the auroral zone. Depending on the effectiveness of the process we may deal with electric fields of about $(10^7 \text{m/sec}) \times 10^{-2}$ weber/m² = 100 volts per meter. Above the current-carrying layer of the auroral ionosphere (80–100 km) the mean free path is long enough to accelerate thermal ions and electrons up to the gas velocity and produce ionization and luminosity in collisions with neutral atoms of the atmosphere. The horizontal current above 100 km would be small since the transverse conductivity applies; the conductivity becomes important in the lower ionosphere where the Hall polarization is discharged when the collision frequency is high enough.

We have two ways of estimating the strength of the shock wave near the Earth. By applying the compression factor we obtain (since $v \propto \sqrt{\text{pressure}}$) $v = (2 \times 10^8 \text{ cm/sec}) \times (A_{\text{initial}}/A_{\text{final}})^{0.2} = 1.3 \times 10^9$ cm/sec. (The straightforward area compression is inversely proportional to B, but we must add the focussing effect evident in Figure 3. We estimate this to introduce a factor of at least 10.)

Another approach is to note that the SC* is produced by the incidence of the shock. We can therefore calculate the shock strength from the magnetic pressure:

$$\tfrac{1}{2}\rho v^2 \geq B^2/8\pi = (0.2G)^2/8\pi \sim 10^{-3} \text{ erg/cm}^3$$

Hence as the shock enters the atmosphere, $v \sim 10^9$ cm/sec.

To estimate the effect of this shock wave at balloon altitudes, we set the energy density equal to the pressure differential; hence Δp is 10^{-3} dynes/cm² compared to an ambient pressure of 10^4 dynes/cm². It might be possible to observe this pressure pulse experimentally. (For a proper analytical treatment of a shock wave in a medium of variable density, see *Chisnell* [1955].)

Appendix 4—Calculation of Main-Phase Ring Current

We will first calculate the motion of a single proton or electron of the characteristics given in Table 1.

(1) For $\alpha_0 = 90°$, that is, for the particle in the equatorial plane, the situation is quite simple (see Fig. 9). Using the methods of *Alfvén* [1950, pp. 13–34] we get (in our notation)

$$V_{\text{drift}} = V_{0\rho} \text{ grad } B/2B$$

For a perfect dipole,

$$\text{grad } B/B = -(3M/r^4)/(M/r^3) = -3/r$$

Hence $V_{\text{drift}} = 3\ V_{0\rho}/2r = 1.5 \times 10^8$ cm/sec at 6.7 Earth radii. Since $\rho \propto r^3$, the drift velocity increases as r^3. The Alfvén approximation breaks down when $\rho \sim R_e$. It is easily seen that the electron contribution to the current is negligible (Table 2).

TABLE 1 – *Basic data on corpuscular radiation*

Item	Proton	Electron
Velocity, V_0	2×10^8 cm/sec	Same
Momentum	6.265 Mev/c	3.41 kev/c
Kinetic energy	20.95 kev	11.38 ev
Ionization range	$\sim 10^{-4}$ g/cm^2	~ 0
Radius of curvature, ρ	$\sim[2 \times 10^4/H]$cm	$10/H$ cm

TABLE 2 – *Longitude drift of particles*

R_e	B	ρ	V_{drift}[a]	$\Delta\lambda$[b]	T[c]		
					$\alpha_0 = 15°$	$\alpha_0 = 30°$	$\alpha_0 = 60°$
Earth radius	gauss	cm	cm/sec	°	sec	sec	sec
1	0.3	7.0×10^4	3.3×10^4	7.4×10^{-3}	4.3	3.8	.32
5	2.4×10^{-3}	8.7×10^4	8.2×10^4	1.8×10^{-1}	21	19	16
6.7	10^{-3}	2.1×10^7	1.5×10^4	3.3×10^{-1}	27	25	22
10	3×10^{-4}	7.0×10^7	3.3×10^4	7.4×10^{-1}	43	38	32
20	3.8×10^{-5}	5.6×10^8	1.3×10^7	3.0	85	75	65
40	4.7×10^{-6}	4.5×10^9	5.2×10^7	1.2×10	168	150	128

[a] Drift velocity in equatorial plane, for particles with $\alpha_0 = 90°$.
[b] Azimuthal advance in a $\frac{1}{2}$-oscillation.
[c] Time for $\frac{1}{2}$ oscillation as a function of α_0.

(2) To deal with particles which oscillate about the equatorial plane ($\alpha_0 \neq 90°$) we again adopt another perturbation method by *Alfvén* [1950, pp. 28–31]. He gives the displacement in longitude of a particle for a quarter-oscillation (see Fig. 10) as

$$\Delta\lambda = (R_e/C_{sl})^3 I_1$$

where $C_{sl} = [M/(mvc/e)]^{\frac{1}{2}}$ the Störmer length corresponding to the particle rigidity and Earth's dipole moment M. For $v = 2 \times 10^8$ cm/sec $C_{sl} = 6.23 \times 10^{10}$ cm. The value of I_1 according to Alfvén varies between 65° and 75°, within wide limits of the amplitude of the oscillation. (It is of interest to note that cosmic ray particles near critical energy perform similar oscillations and can advance in longitude by similar amounts, that is, $\Delta\lambda \sim I$ [see, for example, *Firor*, 1954]. For these high-energy particles the approximation of constant magnetic moment does not hold, hence they are not trapped by the mechanism described above under *Model of main phase of magnetic storm*, and hit the Earth or return to infinity.) Values of $\Delta\lambda$ for varying R_e are given in Table 2.

To calculate the drift velocity in the general case, we must know the time T taken for a quarter oscillation (from the equatorial plane to the reflection point).

Under the adiabatic approximation $\sin^2 \alpha_0/B_0 = \sin^2 \alpha/B$; $B_0 = \mu M/R_e^3$. If we measure z along the line of force (defined by R_e) from the equatorial plane, then we know B and therefore α as a function of z. Also $V_z/V_0 = \cos \alpha$. We can also calculate z_{max}, since there $\alpha = 90°$, and therefore $B = B_0/\sin^2 \alpha_0$. Using α_0 and R_e as parameters, we find T as

$$T = \int_0^{z_{max}} dz/Vz = 1/V_0 \int_0^{z_{max}} dz/\cos \alpha$$

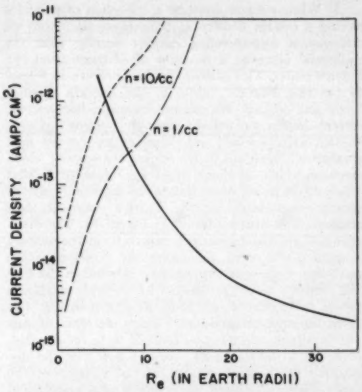

FIG. 14 – Current density in the equatorial plane as a function of distance from the center of the Earth; the solid line shows the maximum current density supportable by the magnetic field gradient; the dashed line shows the maximum current density from considerations of drift velocity; the density is assumed to be one particle per cm^3; the resulting current density has a maximum at about eight Earth radii, which is well within the range in which the Alfvén approximation holds

TABLE 3 – *Calculation of ring current*

R_e	T_{ave}	$\Delta\lambda/T$	Velocity	Current[a] density	Current[b] density
Earth radius	sec	°/sec	cm/sec	amp/cm^2	amp/cm^2
1	4	1.8×10^{-3}	2×10^4	3.2×10^{-15}	1.2×10^{-9}
5	19	10^{-2}	5.6×10^5	6.8×10^{-14}	1.8×10^{-13}
6.7	25	1.3×10^{-2}	9.7×10^5	1.6×10^{-13}	5.8×10^{-13}
10	38	2×10^{-2}	2.2×10^6	3.6×10^{-13}	1.2×10^{-13}
20	75	4×10^{-2}	8.9×10^6	1.4×10^{-12}	7.2×10^{-13}
40	150	8×10^{-2}	3.6×10^7	5.7×10^{-13}	1.8×10^{-15}

[a] Equatorial current density with a particle density of 1/cc in the equatorial plane.
[b] Maximum current density supportable by the field gradient.

Now cos α can be expressed in terms of z, and T is found by integration. Values of T for various values of α_0 and of R_e are given in Table 2. Since T depends only weakly on α_0, we take T_{ave} and use it to calculate the azimuthal drift velocity (Table 3).

We note from Alfvén's treatment that I_1 increases linearly until the latitude of the particle reaches about 30° and then stops increasing. Physically this means that the particles do not advance in azimuth when they are beyond latitude ±30°. Since the time spent in a latitude interval increases as the particle departs from the equator (because of the increasing pitch angle), the drift velocity has a maximum at the equator. Hence the current due to a single particle will show a maximum in the equatorial plane, irrespective of its pitch angle.

(3) When we now consider a collection of particles having a certain density in the equatorial plane, we can plot a corresponding current density near the equatorial plane as a function of distance from the Earth's center. This current density is shown in Figure 14 for two different values of the particle density, $1/cm^3$ and $10/cm^3$. We cannot, however, increase the current density indefinitely, since the current produces its own magnetic field and therefore reduces the field gradient which drives it. By finding the current which produces a field gradient equal and opposite to that which drives it, we can estimate the maximum current density supportable by the Earth's magnetic field gradient. This also is plotted in Figure 14. The intersection of the two curves is found to be in the vicinity of eight Earth radii, indicating the position of the maximum of the ring current. (An increase in the particle density to 10/cc shifts the current maximum inward to about 6 Earth radii, as shown in Fig. 14.) Using the approximation of a linear decrease of current density as a function of latitude from the equator, falling off to zero at $\pm 30°$, we can now plot the distribution of the ring current in the vicinity of the Earth. Figure 11 shows the result of this calculation, assuming a particle density of 1 per cm^3. The total current, about 4×10^8 amp, is twice that required to account for the very largest magnetic storms.

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Classification of Daily Sea-Water Data

SUSUMU TABATA

Abstract—A method is presented for classifying daily observations of sea-water temperature and salinity at five light stations along the coast of British Columbia. In order to summarize the large masses of data collected during the 15 years, 1940–1954, the monthly means are compared to the grand monthly means by passing them through a step filter whose jumps are chosen from integral multiples of the standard deviations. Examples of the use of this classification are also shown.

Observations of temperature and salinity of the surface waters of the British Columbia coast have been made daily at several coastal light stations for varying periods since 1914. They are published annually in manuscript series by the *Pacific Oceanographic Group of the Fisheries Research Board of Canada* [1944–1954].

Utilizing these data, *Pickard* and *McLeod* [1953] have made a preliminary analysis of the general trends of temperature and salinity along this coast using grand monthly means through 13 years and have described their annual cycles in terms of known geophysical principles. Several descriptive reports on these observations have also been made by *Tully* [1937, 1938, 1950, 1952] and *Hollister* [1949, 1951, 1952]. A good deal of the data is currently being used by fisheries biologists in correlating with the abundance or scarcity of particular marine species in the region.

Frequently large masses of data need to be examined and periods of abnormality isolated before such correlations can be made. It appears that the analysis may be facilitated if the data can be summed up by constructing a filtering device that would classify them. In order to provide such a filter the 15 years of data (1940 to 1954 inclusive) are classified using integral multiples of standard deviations.

Daily observations of sea-water temperature and salinity are made at a depth of three feet at the time of high tide occurring during the daylight hours. Each day's observation is about three-quarters of an hour later than the previous one. The time of observation therefore progresses through the day from about 07h 00m to 19h 00m in about two weeks, and variations due to diurnal effects are inevitable. Because observations are made near the shore, they do not necessarily represent the oceanographic conditions away from the shore. Furthermore, the declination effects on the tides and the tidal mixing associated with the tidal currents probably affect the data. But by taking monthly means these effects are minimized, and this period seems to be appropriate for analyses.

Some authors have grouped natural conditions according to arbitrary limits chosen after careful study. An example of this is *Easton's* [1928] classification of winters in Europe. Such classification, though adequate in some individual time series, is not generally satisfactory because it may not be applicable or comparable to other series. There is also a lack of objectivity in the selection of the limits. However, if limits are derived from statistical elements, most of the objections disappear. *Conrad* [1953] has separated severe and mild winters in Europe by using standard deviations as a deciding limit in the classification.

The daily sea-water observations made in British Columbia represent a number of individual time series. The limits of the significant variations of these series vary with stations and with seasons; for instance, a fluctuation of temperature of a few degrees may be considered as normal and random at one station while it may be very significant at another. The same reasoning applies to fluctuations in different seasons. These considerations led to the use of a statistical filter.

Method of classification—Although records are available from some localities for more than 20 years, the data from most of the stations from about 1940 onward appear to be most consistent. In this study only the data from 1940 to 1954 inclusive from each station are considered so that they have equal statistical weight.

The grand monthly means obtained from 15 years of observation are assumed to represent the average state during this period. Actually, if data are available, an average based on a longer period may be more stable since the means are likely to be more stable.

The magnitudes of the monthly means are compared to the grand monthly means by passing them through a step filter whose jumps are chosen from commonly used multiples of the standard deviations (σ, 2σ). The resulting codification is shown

TABLE 1 – *Statistical limits used in classification*

Code Letter	Limits	Remarks
+C	$>+2\sigma$	Much above average
+B	$+\sigma$ to $+2\sigma$	Above average
+A	Mean to $+\sigma$	Average
A	Mean	
−A	Mean to $-\sigma$	
−B	$-\sigma$ to -2σ	Below average
−C	$<-2\sigma$	Much below average

in Table 1. This is a coarse filter, but if a more detailed treatment is required the steps can be arranged in multiples of $\sigma/2$.

Discussion—The grand monthly mean values of the sea-water data and their standard deviations at five of the stations (Fig. 1) from the 15 years' data (1940–1954) are shown in Tables 2 and 3 and the classified data on Figures 2 and 3.

It is fairly easy to select the periods of maximum deviations of temperature and salinity that occurred at these stations during the last 15 years.

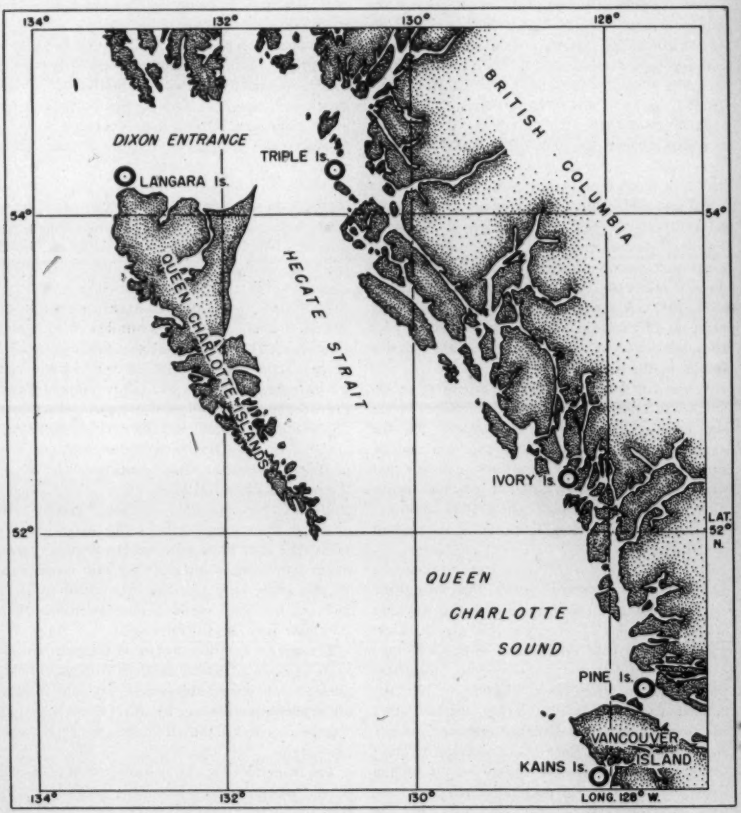

FIG. 1 – Chart showing location of light stations Langara, Triple, Ivory, Pine, and Kains

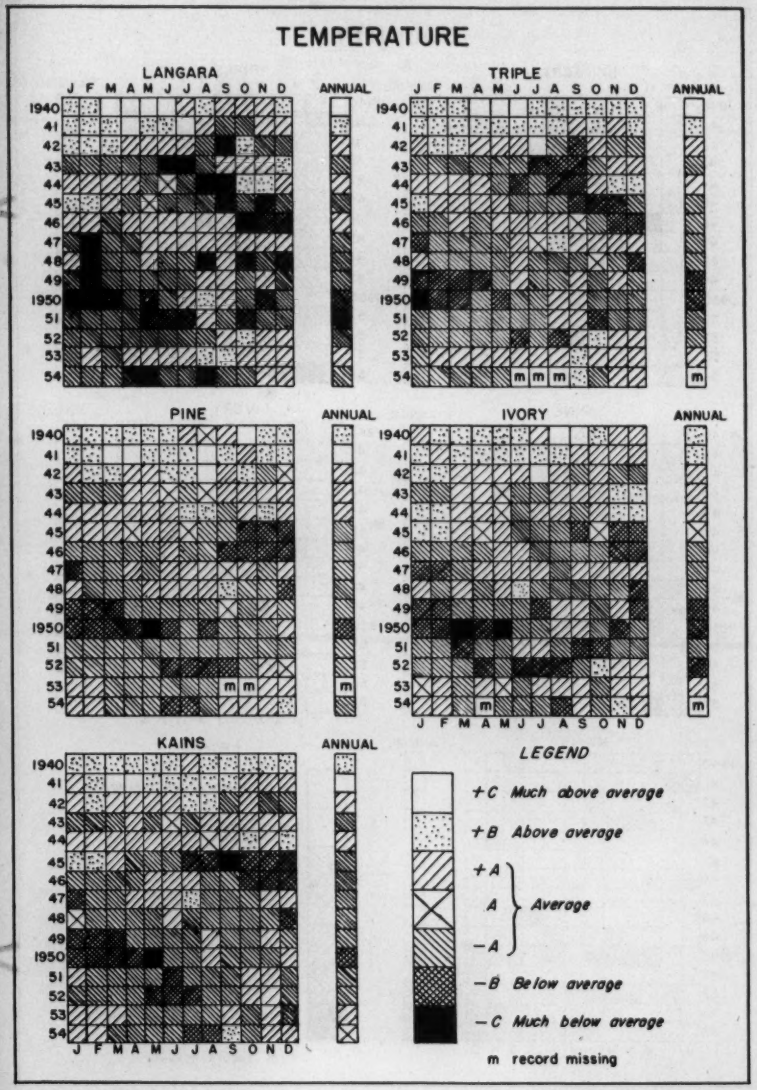

FIG. 2 – Classification of sea-water temperatures at the five light stations for the period 1940 to 1954

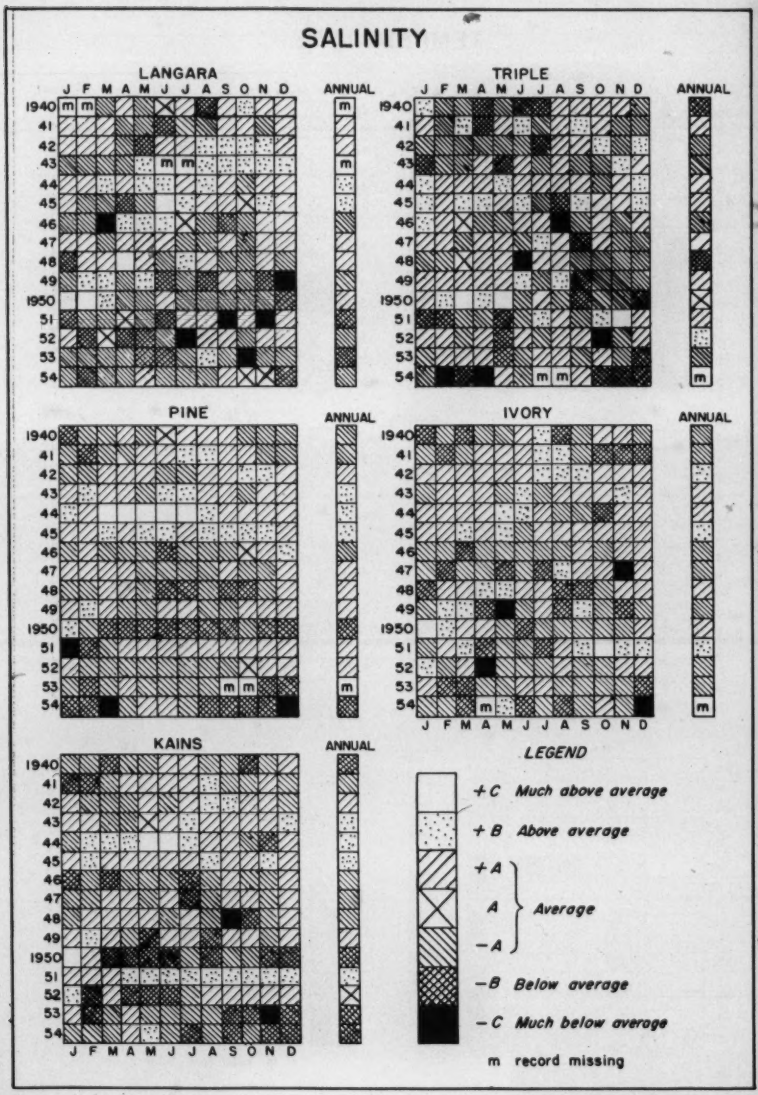

FIG. 3 – Classification of salinity at the five light stations for the period 1940 to 1954

TABLE 2 – *Grand monthly means* ($\bar{T}$) *and standard deviations* (σ) *of the surface sea temperatures* (°F) *at five light stations, 1940–1954*

Light station	Item	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
Langara	$\bar{T}$	43.1	42.8	43.3	44.7	47.2	49.6	52.2	52.7	52.5	51.1	47.4	44.9
	σ	2.3	1.8	1.6	1.4	1.2	1.1	1.2	1.5	1.2	0.9	1.4	1.6
Triple	$\bar{T}$	44.4	43.7	43.6	44.8	47.9	51.9	54.3	54.6	52.9	50.7	48.2	46.2
	σ	2.3	2.0	1.9	1.6	1.4	1.2	1.1	0.8	0.8	0.6	1.1	1.6
Ivory	$\bar{T}$	43.6	43.2	43.9	46.4	50.7	54.9	57.7	58.1	56.1	51.7	47.6	45.0
	σ	1.7	1.6	1.4	1.8	1.3	1.2	1.1	0.7	1.1	0.7	1.2	1.5
Pine	$\bar{T}$	45.4	45.0	45.2	46.1	47.5	48.8	49.9	49.8	49.5	49.4	48.3	46.5
	σ	1.2	1.4	1.2	1.3	1.1	0.8	0.7	0.5	0.5	1.0	1.4	1.0
Kains	$\bar{T}$	45.9	45.5	46.2	47.7	50.3	52.8	54.8	55.6	55.3	52.7	49.4	47.3
	σ	2.1	1.8	1.5	1.6	1.2	1.4	1.4	1.0	1.4	1.0	1.5	1.6

TABLE 3 – *Grand monthly means* ($\bar{S}$) *and standard deviations* (σ) *of the surface salinities* ($S‰$) *at five light stations, 1940–1954*

Light station	Item	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
Langara	$\bar{S}$	32.21	32.27	32.26	32.32	32.32	32.30	32.18	32.24	32.15	32.16	32.01	32.08
	σ	0.27	0.16	0.18	0.14	0.11	0.20	0.15	0.24	0.38	0.32	0.15	0.21
Triple	$\bar{S}$	31.72	31.76	31.79	31.75	30.67	28.98	29.50	30.18	30.84	31.39	31.55	31.69
	σ	0.29	0.27	0.20	0.28	0.57	1.16	0.93	0.58	0.35	0.40	0.24	0.27
Ivory	$\bar{S}$	29.79	29.87	29.96	29.23	28.94	27.51	26.45	26.59	27.47	27.50	28.28	28.81
	σ	0.78	0.67	0.75	1.04	0.91	1.28	1.12	1.28	1.40	1.37	0.94	0.82
Pine	$\bar{S}$	31.42	31.40	31.54	31.68	31.79	31.87	31.79	31.86	32.01	32.04	31.75	31.50
	σ	0.31	0.27	0.25	0.21	0.19	0.23	0.21	0.18	0.25	0.20	0.31	0.36
Kains	$\bar{S}$	29.53	29.32	29.89	30.14	30.61	31.40	31.82	32.10	31.69	30.50	29.64	29.02
	σ	0.73	0.88	0.76	0.69	0.60	0.37	0.44	0.36	0.56	0.87	0.97	0.77

There is a marked difference between the temperatures in the period a decade apart (Fig. 2). In the years 1940 and 1941 the temperatures are consistently greater whereas in 1950 they are lower than the means.

There appears to be a coherence in the temperature events; that is, the warmer months are followed by warmer months, the colder by colder months, and so on. This is similar to meteorological events which tend to cohere rather than occur as isolated incidents [*Brooks* and *Carruthers*, 1953]. They not only persist from month to month but tend to cluster from year to year. Apart from this, no obvious trend in the year to year variations could be detected. A more or less similar type of coherence occurred in the salinity events. In the years 1943 and 1944 the water was generally more saline and in 1953 and 1954 it was less saline than the means.

The classification of these variables is a methodological example of grouping the data and determining their major variations, but it provides an easy reference for outlining the general oceanographic state.

In the investigation of marine life, the reason for occurrence or absence, or for fluctuation in abundance, of species is frequently sought in terms of oceanographic conditions. Various topics on the physical conditions in the sea in relation to fishes, such as temperature and salinity relating to spawning, temperature, and development of larvae, etc., have been discussed by *Tait* [1952]. *Ketchen* [1956] showed correlation between monthly mean sea temperatures and the sizes of year-classes of groundfish in Hecate Strait.

The present classification would provide a quick way of recognizing the first-order correlation and may be used as a guide for a more detailed study.

When series of quasi-synoptic oceanographic surveys extending for a period of a month or so are made in a locality, one of the routine analyses involves the examination of the seasonal variations during that period. There are instances where the situation is generalized and conjecture made that the condition is typical. In some cases such assumptions are justified, but in others the conditions may be exceptional rather than typical. It may be possible that the classification of daily sea-water data may facilitate the generalization of such cruise data.

In Table 4 is shown the classification of the surface sea-water temperature and salinity during

TABLE 4 – *Classification of monthly sea-water data during Hecate cruises 1954–1955*

Item	Station	1954												1955							
		J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A
Temperature (°F)	Langara	−A	−A	−A	−B	−B	−A	−A	−B	−A	−A	+A	+A	+A	+A	−A	−A	−B	−B	−C	−A
	Triple	A	−A	−A	−A	−A	−	−	−	+B	−A	+A	+A	+A	+A	−A	−A	−A	+A	−A	−C
	Pine	+A	+A	−A	−A	−A	−B	−B	−A	+A	+A	+A	+B	−A	+A	−A	−A	−A	+A	−B	−B
	Ivory	+A	+A	−A	−	−A	−A	−A	−B	+A	+B	−A	+A	+B	+B	+A	−A	−B	−A	−A	−A
	Kains	+A	+A	−A	−A	−A	−A	−B	−B	+B	−A	+A	+A	+A	−A	−B	−A	−B	−B	−B	−C
Salinity (‰)	Langara	−A	−B	−A	−A	+A	−A	−A	−A	+A	A	A	−B	−A	−C	−A	−C	−C	−C	−A	−A
	Triple	−A	−C	−B	−C	+A	−A	−	−	+A	−B	−B	−B	+A	−C	−B	−B	+B	+A	−C	−A
	Pine	−B	−B	−C	−A	+A	+A	−A	−B	−B	−B	−B	−C	−B	+A	+B	+B	+B	+B	+B	−A
	Ivory	−A	−A	−B	−	+B	−B	−A	−B	−A	+A	−A	−C	−B	−B	+A	+A	+A	+A	−A	−B
	Kains	−A	−A	−A	+A	+B	−A	−B	−A	−B	−A	−B	−B	−A	+A	+C	+B	+B	+A	+A	−A
		Cruise numbers			↑	54-1→		54-2→	54-3→			54-4→			55-1→		55-2→		55-3→	↑	
					Surveys																

January 1954 to August 1955 relative to the average conditions of the previous 15 years. During the period of the surveys, the daily sea-water data indicate that the sea temperature was generally lower and the salinity also less than those of the respective means of the previous 15 years. The water was particularly colder in the summer of 1954 and somewhat warmer in the winter of 1954–1955. Salinity was also lower in the summer of 1954 but not as marked as in the winter of 1954–1955 when it was particularly low. This latter is probably the most outstanding feature of the difference in the conditions from that of the means. One interesting feature of this less saline water is that it occurred earliest in the southern stations.

Since the summer temperature was lower and the winter temperature higher than the means, the amplitude of the annual cycle was small, and therefore the conclusion based on these as representing average states could be misleading.

At Pine Island the salinity was low in the latter half of 1954 but was high in the first half of 1955. Thus the annual amplitude was much larger than in an average year and could not be considered as typical of the average state.

These are examples in which the classification may be used. It defines both the normal years when conditions are most representative and abnormal years when some peculiarities may have occurred. It also provides indices of the general oceanographic condition in the region, and cruise data collected during any given time may be referred to these and suitable adjustment made on these data for generalization.

When large amounts of data are to be processed and examined, as in the case of daily sea-water observations, this method has a particular advantage in the relative ease in which classification and then comparison can be made.

Acknowledgments—The author is indebted to D. A. Still and K. H. Austin for executing many of the calculations and to J. P. Tully for his valuable suggestions and criticisms during the course of the investigation.

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A Criterion for Selection of Length of Record for a Moving Arithmetic Mean for Hydrologic Data

ROBERT T. BEAUMONT

Abstract—In forecasting runoff a reliable base period is usually needed for reference. A procedure has been derived by which an objective selection as to the best length of record can be made for computation of a moving arithmetic mean. Results are given for several records of precipitation and runoff at stations in the western United States.

Introduction—In almost every analytical problem where the object is to predict future events concerning meteorological, hydrologic, and climatological data, one is confronted with making a decision as to length of record to use which will be most representative of the next event. In many instances the length of record may be so short that it must be used in its entirety. However, there are records of streamflow, precipitation, and temperature of considerable length, that is, 60 to 80 years. Noticeable 'trends' or 'cycles' are frequently found in records of this length. Efforts to use these trends to estimate future events have not been successful and little use has been made of them since physical factors causing such trends or cycles have been obscured. A procedure is needed to determine length of record to use to compute a representative moving arithmetic mean to best estimate the next event.

Such a procedure has been derived by the author and is described in this paper.

Computation of the average error mean square (AEMS)—The following quantity has been derived and is defined as the average error mean square (AEMS) and represented by the symbol ϕ. It is computed by the following

$$\phi = \left\{ \frac{\sum_{(i=1)}^{i=(n-k)} \left[\frac{X_1 + X_{(i+1)} \cdots X_{(i+k-1)}}{k} - X_{(1+k)} \right]^2}{n-k} \right\}$$

where k is number of years used in the moving means; for convenience an interval of five years was used to compute the moving mean; thus the values of k were 5, 10, 15, 20, 25, 30, 35

n is number of years in record

X_i is i^{th} year measurement

Values for the AEMS are plotted against the years in k used to compute the AEMS. The number of years which gives the lowest value of AEMS can be taken as the best length of record to use for a moving arithmetical mean. Values of AEMS were computed at intervals of five years for k. This selection was made in order to facilitate computations. It is acknowledged that computation of AEMS for consecutive values of k would give a slightly different distribution than is obtained when computing AEMS for five year interval of k. Intuitively it can be seen this difference would be slight except perhaps for values of k less than ten.

AEMS values were computed from records of annual river flow and precipitation measurements in the West. Computations were made for the Columbia River at The Dalles, Oregon; Spokane River at Spokane, Washington; and the Salt River at Roosevelt Dam, Arizona.

AEMS was computed for the following precipitation stations at Albany, Ashland, Portland, and The Dalles, Oregon; Moscow, Idaho; Spokane, Washington; and Cheyenne, Lander, Laramie, and Fort Laramie, Wyoming.

These particular precipitation and river gaging stations were chosen at random, except for scanning the record to assure sufficient length to provide 30 and 35 year means. The records were taken 'raw' from their published sources without correction or adjustment. Plottings of the AEMS against the number of years used to compute the moving mean are given for the river flow and precipitation data in Figures 1 and 2. Inspection of

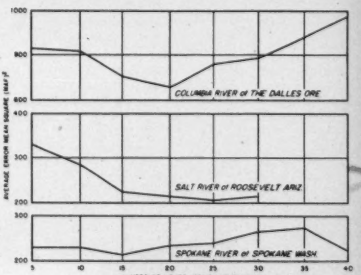

FIG. 1 - Distribution of the AEMS for western rivers

the individual graphs reveals that in all instances some period shorter than the longest available moving mean will estimate the next year more accurately. For the three rivers the period ranges from 15 to 25 years (Fig. 1). A composite graph (Fig. 3) was made of the river flow data using AEMS as standard measure. This graph indicates that a 15-year mean is the best. Similar analysis for the precipitation data reveals that a 20-year (Fig. 4) base is best for a moving mean.

Interpretation of results—Inspection of these graphs indicates that the best moving mean is one with about 15 to 20 years of record. Moving means based on records of greater or lesser length than this result in a larger AEMS.

This procedure provides a method by which the best period for a moving mean can be determined from the record itself. This period will produce a mean which will be most representative of the next occurrence. It is not clear why 15 or 20 years should provide the best mean.

A great many more computations of AEMS should be made on similar climatological and hydrological data to ascertain if the 15–20 year is the best period, or whether there are other periods which give a lower AEMS. Then these data should be examined to see if there are other parameters by which they could be classified (that is, climatic parameters).

There doubtless are sound physical reasons why the longest hydrologic record does not necessarily give the best estimate of the next event. Where

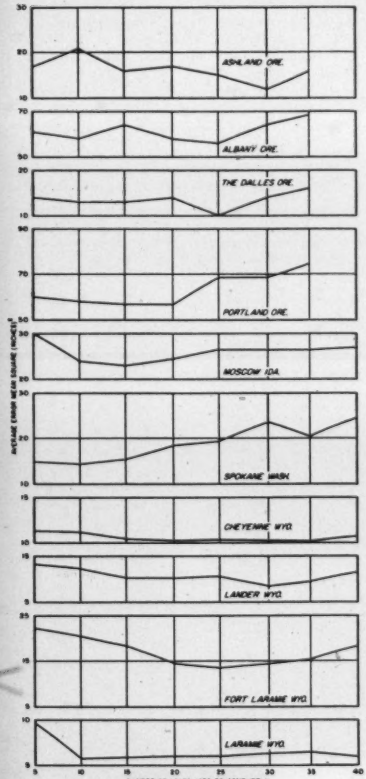

FIG. 2 – Distribution of the AEMS for western precipitation stations

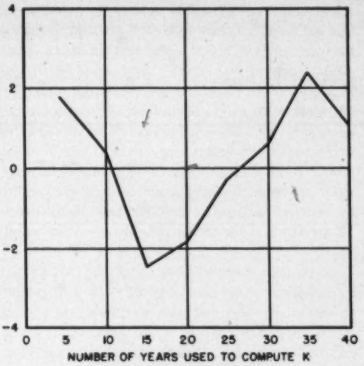

FIG. 3 – Composite graph of distribution for western rivers, AEMS plotted in standard measure

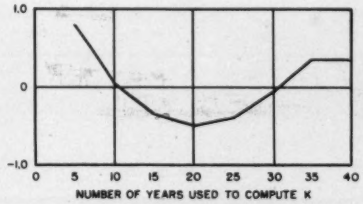

FIG. 4 – Composite graph of distribution for western precipitation stations, AEMS plotted in standard measure

events are even remotely related by persistence, the more recent years of record usually produce a more accurate estimate of the next event. In recent years measurement errors have been reduced considerably from what they were in earliest records. Physical controls on hydrologic elements are becoming more complex because of man's greater utilization of hydrologic resources. Thus a recent record is more representative of future occurrence than one based on early events when there was little or no human control and utilization of resources. These effects favor the use of only the more recent data.

In summation, the plotting of the AEMS for hydrological and climatological data will permit choosing the best period for computation of a moving arithmetic mean. It will also provide a procedure for selecting a length of period to use for a moving regression analysis, as suggested by *Wilm* [1950].

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Minimum Water Yield from Small Agricultural Watersheds

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Abstract—This paper presents methods of analyzing and reporting data on minimum runoff from small agricultural watersheds of 29 to 17,540 acres near Coshocton, Ohio. From 18 years of field records of precipitation and runoff, a relationship was established to provide a means of estimating, from a 46-year precipitation record, 12-month minimum runoff values for recurrence intervals of two to 100 years for this watershed size range. The actual 18-year field records of runoff were used to develop minimum runoff values for periods of one to 12 months. Seasonal occurrence of the four lowest values and the duration of minimum flow throughout the period of record were developed. Minimum five-day stream flow for months of June, July, and August for each year of record is shown. This paper does not attempt to present all the results of this study as the data would be too voluminous. Sufficient data are shown to illustrate the methods used.

The nation's population and urban, industrial, and agricultural development have reached a stage of growth where local water supplies are increasingly failing to meet the demand. In earlier days water withdrawals from streams or underground sources had little effect on other people. It is not uncommon now to read where individuals and organizations have been enjoined from withdrawing water from upstream channels, as such have seriously impaired the activities of downstream water users.

The urgency of this water problem has been recognized in many areas. In Ohio, for example, the Governor established in 1954 an Advisory Committee on Ohio's Water Resources, a board of consultants for all phases of water supply, use, and disposal. One of the results of this Committee's activities has been the recommendation for a water plan for each of Ohio's numerous watersheds. Such plans are expected to provide a broad basis for water-use programming. As such, they would of necessity include estimates of the water resources and future demand for water for each river basin.

Estimates of the reliable and usable water yield in the larger streams of a State may be made from long-time records collected by the U. S. Geological Survey. As industry continues to disperse into the headwater areas, as upstream urban developments increase in size, as rural water usage increases, and as irrigation increases, the demand for proper quantitative estimates of dependable water supply from the smaller watersheds becomes more urgent. In this field of study, basic runoff data from small agricultural watersheds are noteworthy for their scarcity and brevity of record.

The terms 'water yield' and 'runoff' or 'stream flow' have generally been used synonymously. In this paper, the data used represent only runoff and stream flow, that water available for use on the land surface at the point gaged. It does not include deep percolation. Some of these small agricultural watersheds actually yield large quantities of gravity water percolating to ground-water reservoirs. Some of this ground water seeps to the land surface at lower elevations and forms an important part of runoff or stream flow, especially on the larger watersheds.

It is the purpose of this report to present methods used in the analysis of runoff data gathered at a Watershed Hydrology Station of the U. S. Soil and Water Conservation Research Branch near Coshocton, Ohio.

Description of the area—As shown in the insert on Figure 1, this Station is representative of much of the land in this section of Ohio, western Pennsylvania, West Virginia, and Kentucky. The soils of this area are residual, developed from shale, sandstone, and limestone. The depth of topsoil is usually less than seven inches. Land slopes range from six pct to over 35 pct; the average for the larger watersheds being about 15 pct. At various depths beneath the hilly land surface are layers of coal and impervious clay. Percolating waters accumulate on top of the clay, forming perched water tables. This water flows slowly in a lateral direction until it reaches the land surface on the lower elevations of the slopes. There it becomes stream flow and is measured as runoff at the various stream gages.

Vegetative cover of the watershed areas is comprised of about 25 pct woodland, 55 pct grassland (both permanent and rotation), and 20 pct cultivated. Cultivated land is about half row crop and half small grain. Changes in land use on most of the watersheds during the period of record have

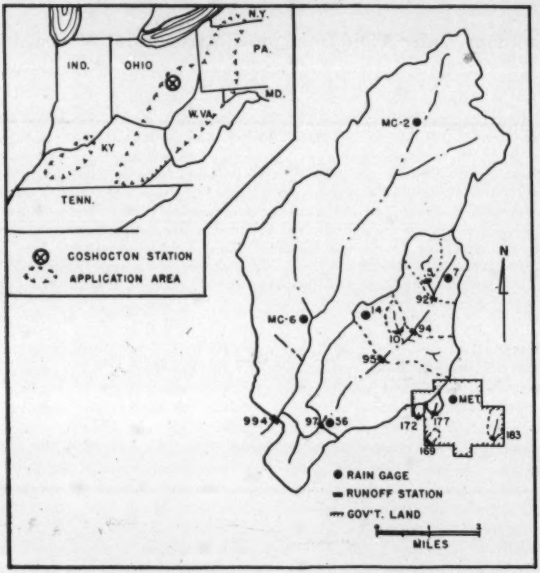

FIG. 1 – Soil and Water Conservation Research Station, Coshocton, Ohio

not been great enough to cause runoff variation. Watersheds from which data are used herein are comparable in physical condition: soils, slope, and cover

The government land as shown on Figure 1 is a block of farms totaling 1047 acres. Gages measure the flow of water from areas of one to 303 acres on this tract. To the northwest and adjacent to this government tract is a watershed in which stream gages measure water flow from 122 to 4581 acres. Below the point where this stream joins a larger one, a gage records the water flow from a 17,540-acre drainage basin. This gage is operated by the U. S. Geological Survey, Surface Water Branch. All other gages are maintained by Agricultural Research Service.

Automatic recording rain gages in these areas provide records of precipitation rates and amounts for every storm.

Period of record—For the larger watersheds, the period of record is 1938–1955. For some of the smaller watersheds, the record began in 1941. Where such information is important in the interpretation of the results, the years of record appear on the figure.

A study of the 46-year precipitation record, 1910–55, at Coshocton, Ohio, (Fig. 2) shows that the years 1938–55 have averaged somewhat below the 46-year mean of 39.94 inches. There were nine years above average and nine years below average. Precipitation for 1944, 1953, and 1954 was extremely deficient. In fact, of the three years in 46 having 30 inches or less precipitation, two occurred in the period of record 1938–55. Our small sample has a lower mean than that for the 46-year period. It is likely, therefore, that estimates of minimum runoff based on the short record may be somewhat biased, and err on the conservative side. Longer records will improve the estimates.

In this report, yearly precipitation and runoff values are given for the water year October 1 to

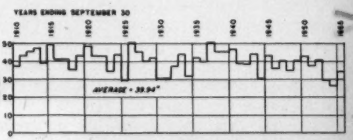

FIG. 2 – Forty-six years of precipitation, 1910–55

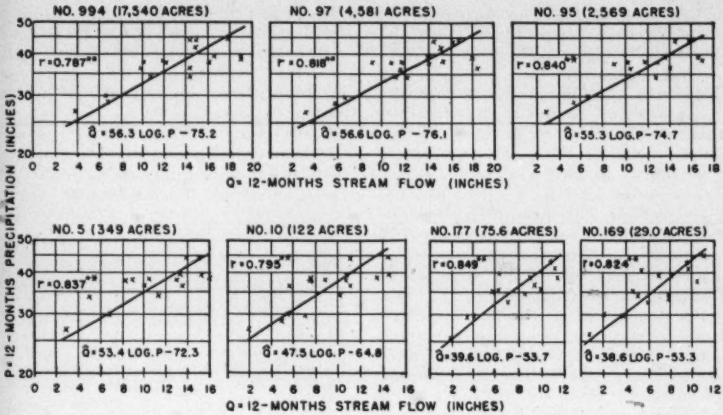
NO. 994 (17,540 ACRES)
NO. 97 (4,581 ACRES)
NO. 95 (2,569 ACRES)
NO. 5 (349 ACRES)
NO. 10 (122 ACRES)
NO. 177 (75.6 ACRES)
NO. 169 (29.0 ACRES)
P = 12-MONTHS PRECIPITATION (INCHES)
Q = 12-MONTHS STREAM FLOW (INCHES)

FIG. 3 – Precipitation-runoff relationship for seven watersheds by water years October–September 1938–55

September 30. As soil-moisture storage, groundwater levels, and stream flow are usually at a minimum on or near September 30, correlation between these values and precipitation are expected to be influenced only slightly by moisture carry-over affects from year to year.

Runoff values—Runoff in this report is that amount of water flowing in surface streams at the outlet of the watershed under consideration. Runoff values are given in units of inches and as such, they represent that depth of water on the entire watershed area if the total stream flow for the period under study was spread out evenly over the entire drainage basin. Both precipitation and runoff are therefore expressed in the same units.

Runoff for the water year—The water-supply engineer may feel that 18 years of record is not enough to provide him with reliable data on dependable runoff. To meet his need, a 46-year runoff-frequency record was synthesized. In order to make this possible, relationships between yearly precipitation and runoff had to be developed. These are shown for Watersheds 994 (17,540 ac), 97 (4581 ac), 95 (2569 ac), 5 (349 ac), 10 (126 ac), 177 (75.6 ac) and 169 (29.0 ac) on Figure 3. Of all the various regressions attempted, the relation of log P to Q gave the best fit to these data. By this type of plotting (log precipitation with arithmetic runoff scales) more weight could be given to the low values and less to the highest ones, as it was desired to arrive at the best estimate of minimum flow, yet use all the data available. This shows that when precipitation values reduced from 35 to 30 inches (Watershed 994) runoff values reduced 3.7 inches, and a precipitation reduction from 30 to 25 shows a corresponding reduction in runoff of 4.4 inches. Within the range of data and at the lower end of the relationship, a uniform reduction of precipitation resulted in greater reduction of runoff.

Next step in the process to estimate 12-month runoff values for various recurrence intervals was the development of a precipitation-frequency relationship for the 46-year Coshocton record (Fig. 4). This curve was computed by the *Hazen* [1930] method. The 1953–54 precipitation value

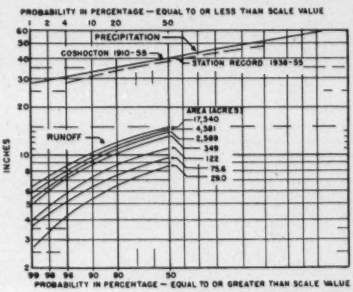

FIG. 4 – Precipitation and runoff frequency curves for watersheds of 29 to 17,540 acres, 12 months, October–September

of about 26 inches (Fig. 2) would have a probable recurrence of once in a period of over 100 years. The frequency relationship of the 18-year station record lies slightly below that for 46 years.

Also shown on Figure 4 are runoff-frequency curves for seven watersheds of different size. Precipitation values for 50, 80, 90, 96, 98, and 99 pct of time were taken from the 46-year precipitation curve (Fig. 4) and substituted for P in the precipitation-runoff formulas for each watershed appearing in Figure 3. The estimated runoff values Q thus derived were considered as estimates of the true runoff values associated with the corresponding precipitation value. Multiple regression equations using size and frequency were then used to obtain the smoothed runoff curves appearing on Figure 5. These curves represent the best evaluation of probable 12-month minimum runoff. Plotted points are from the Hazen values computed for the runoff curves shown on Figure 4. Curves on Figure 5 are computed from: $Q = 5.04 \log \text{area} - 0.56 (\log \text{area})^2 - 3.98 \log \text{years} - 0.15 (\log \text{area}) (\log \text{years}) + 3.89$.

Although the exceedance frequency (bottom scale, Figure 4) may be used more often, there may be times when the 'equal to or less than' scale (top of Figure 4) may be desired. This latter scale shows that a water-year runoff of 6.8 inches or less for 4581 acres may occur only two per cent of the time, or two years in 100.

Our best estimates of 12-month runoff for various exceedance intervals and for four different watersheds taken from Figure 4 appear in Table 1. This means, for example, that runoff equalled or ex-

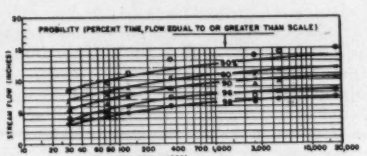

FIG. 5 – Minimum 12-month runoff-frequency-watershed size relationship

TABLE 1 – *Estimates of 12-month runoff from watersheds of different area from Figure 4*

Watershed area	Exceedance interval	Runoff amount
ac	year	inch
4581	98	6.8
	96	8.0
	90	9.7
	80	11.7
122	98	4.8
	96	5.8
	90	7.2
	80	8.7
75.6	98	4.3
	96	5.2
	90	6.3
	80	7.5
29.0	98	3.3
	96	4.2
	90	5.3
	80	6.4

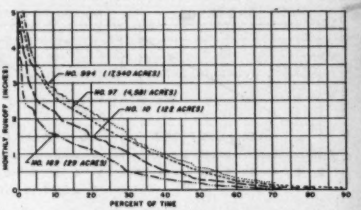

FIG. 6 – Monthly runoff duration curves for watersheds of 29 to 17,540 acres, 1938–54

TABLE 2 – *Minimum water yield from watersheds of different sizes and for periods of from one to 12 months, 1941–54*

Length of period	Order no.[a]	Minimum water yield for watersheds of acreage shown						
		17,540[b]	4,581[b]	349[c]	122[c]	75.6[c]	74.2[c]	29.0[c]
Month		inch	inch	inch	inch	inch	inch	inch
1	1	0.005	0.0007	0.0029	0.0008	0	0	0
	2	0.006	0.0016	0.01	0.02	0	0	0
	3	0.009	0.0039	0.01	0.02	0	0	0
	4	0.01	0.01	0.01	0.02	0	0	0
	5	0.02	0.01	0.01	0.03	0	0	0
	6	0.02	0.01	0.01	0.03	0	0	0
	7	0.03	0.01	0.01	0.04	0	0	0
3	1	0.03	0.0056	0.0088	0.01	0	0	0
	2	0.07	0.04	0.03	0.07	0	0	0
	3	0.10	0.04	0.04	0.09	0	0	0
	4	0.11	0.05	0.05	0.10	0	0.0059	0
	5	0.13	0.10	0.10	0.11	0	0.01	0.0003
	6	0.13	0.11	0.10	0.17	0	0.07	0.0007
	7	0.15	0.12	0.13	0.18	0.0008	0.07	0.0043
6	1	0.29	0.13	0.10	0.18	0.01	0.05	0.02
	2	0.38	0.29	0.18	0.21	0.02	0.05	0.08
	3	0.53	0.46	0.49	0.49	0.04	0.19	0.11
	4	0.61	0.49	0.50	0.61	0.08	0.24	0.12
	5	0.68	0.61	0.53	0.71	0.08	0.41	0.17
	6	0.84	0.80	0.57	0.77	0.11	0.51	0.22
	7	0.97	0.93	0.72	0.85	0.20	0.61	0.37
12	1	3.76	3.64	3.12	2.16	1.99	1.91	0.82
	2	5.13	4.95	4.56	2.78	2.13	2.16	0.94
	3	6.50	6.01	5.39	4.86	3.38	3.65	2.00
	4	6.61	8.40	7.57	5.06	4.03	7.13	3.82
	5	7.72	8.57	8.07	6.23	5.54	7.83	4.77
	6	8.30	9.14	8.17	6.57	6.25	7.97	5.08
	7		9.93	8.92	7.52	6.46	8.60	5.23

[a] Lowest value first.
[b] Seventeen years of record, 1938–54.
[c] Fourteen years of record, 1941–54.

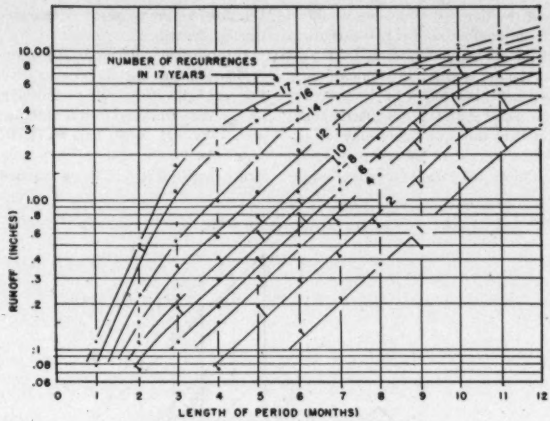

FIG. 7 – Number of times in 17 years that runoff was equal to or less than the indicated amounts for periods of one to 12 months, Watershed 97, 4581 ac, 1938–54

ceeded 96 per cent of the time from the 4581 acre watershed would be 8.0 inches. This also means that on the average four times in 100 years, or once in 25 years the 12-month flow is likely to be 8.0 inches or less.

It is evident that in this locality the dependable runoff values decrease as the drainage area becomes smaller. This is illustrated in Figure 5 where the runoff values for various recurrence intervals for different sized watersheds were assembled on the same plot. The decrease in runoff from 20,000-acre watersheds to 400-acre watersheds for the same frequency appears to be fairly small, yet noticeable. This decrease is more strikingly evident as the watershed sizes diminish from 400 to 30 acres. This minimum water-yield relationship to watershed size, in general, should apply to other areas where deep percolation is not measured (nor available water yield) on the small watershed, but is available as surface flow from seepage in the larger watersheds.

Runoff (1 to 12 months)—Yearly runoff data are in some cases not adequate to solve many water-supply problems. Monthly data are required. Monthly runoff duration curves are shown on Figure 6. The monthly runoff duration-curve study would have application to water-supply problems where little or no provision is made for storage in srteam reservoirs. In many cases reservoirs can be provided for storage of water to meet the needs during the periods of extremely low runoff. In such cases, the water-supply engineer needs runoff values for consecutive months in periods of several-months duration. To meet this need, minimum runoff values for watersheds of 29 to 17,540 acres for periods of 1, 3, 6, and 12 months, irrespective of calendar or water year, have been compiled and are listed in Table 2.

Runoff data for the water year as shown on Figure 5 indicate that the runoff equalled or ex-

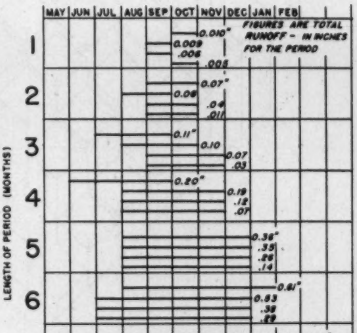

FIG. 8 – Seasonal occurrence of minimum runoff (lowest four values in 17 years) for periods of one to seven months, Watershed 994, 17,540 ac, 1938–55

ceeded 98 pct of the time for 4581 acres would be 6.80 inches. The minimum recorded 12 consecutive-month flow (Table 2) for this watershed was 3.64 inches. The minimum 12-consecutive-month runoff irrespective of the calendar is likely to be less than that for the water year. It is possible that runoff values lower than this 3.64 inches may not occur oftener than one time in 100 years or more. Seventeen years of record are not enough to establish this frequency value to the degree of reliability usually desired.

It is possible to derive an approximate frequency evaluation from the runoff data given in Table 2. For example, the six-consecutive-month values for the 122-acre watershed beginning at the lowest, are: 0.18, 0.21, 0.49, 0.61, 0.71, 0.77, and 0.85 inch. The lowest value of 0.18-inch could be assigned a frequency of being reached or exceeded

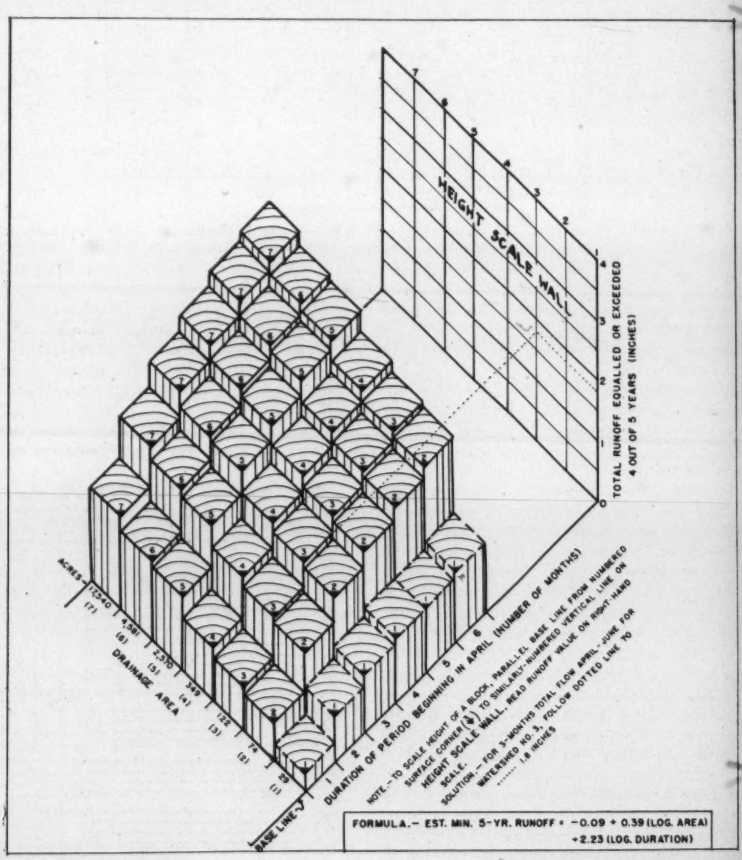
WEIGHT SCALE WALL
TOTAL RUNOFF EQUALLED OR EXCEEDED 4 OUT OF 5 YEARS (INCHES)
DURATION OF PERIOD BEGINNING IN APRIL (NUMBER OF MONTHS)
DRAINAGE AREA
ACRES
BASE LINE
NOTE.- TO SCALE HEIGHT OF A BLOCK, PARALLEL BASE LINE FROM NUMBERED SURFACE CORNER (6) TO SIMILARLY-NUMBERED VERTICAL LINE ON HEIGHT SCALE WALL, READ RUNOFF VALUE ON RIGHT-HAND SCALE.- FOR 3-MONTHS TOTAL FLOW APRIL-JUNE FOR WATERSHED NO. 3, FOLLOW DOTTED LINE TO ..... 1.8 INCHES
FORMULA.- EST. MIN. 5-YR. RUNOFF = -0.09 + 0.39 (LOG. AREA) +2.23 (LOG. DURATION)

FIG. 9 – Estimated runoff expected to be reached or exceeded 80 pct of the time for durations of one to six months beginning with April from watersheds of 29 to 17,540 ac.

every year in 15, or 93 pct of the time. The second lowest value of 0.21 inch receives an exceedance frequency 14 out of 15 years, or 87 pct of the time. The seventh lowest value of 0.85 received a 50 pct probability.

The relationship between runoff from a 4581-acre area and length of period from one to 12 months is shown graphically on Figure 7. Whereas only the seven lowest values are given in Table 2, all 17 lowest runoff values (period of record) are shown on Figure 7. The curve labeled 1 shows the approximate position of the minimum runoff values for periods of six to 12 months. Some of the values for periods of less than six months were too small to be shown on this figure. They can be obtained from Table 2. From this figure, one can obtain an evaluation of the runoff and frequency for different-length periods. Reading the value from the curve, the 'equal to or less than' 8-month runoff for once in 17 years is 0.38 inch; that for twice in 17 years or once in about 8½ years, 0.84 inch; once in 4.2 years, 1.5 inches; once in 2.8 years, 2.0 inches; once in 2.1 years, 2.7 inches, and once every year, 8.1 inches.

If one was interested in the length of period to produce a total flow of, say 0.4 inch, the values could be read from Figure 7. For once in 17 year recurrence or exceeded 16 out of 17 years, the period would be about eight months; the once in 8½ years or exceeded 15 out of 17 years, about seven months would be required to give a total flow of 0.4 inch. In the first case, curve 1 is used and in the second, curve 2.

Seasonal occurrence of low flow—The water user is often interested in knowing when to expect the lowest runoff. For example, the irrigating farmer needs a dependable water supply when vegetation's water demand is the greatest. The seasonal occurrence of the four lowest runoff values for periods of one to seven months duration for the 17,540-acre watershed is shown graphically on Figure 8. In this case, the low-flow periods were concentrated in the late summer and fall.

For some purposes it may be desirable to develop values of dependable runoff for different recurrence intervals, according to seasonal expectancy. Such a relationship appears on Figure 9, the estimated runoff reached or exceeded 80 pct of time for durations of 1 to 6 months beginning in April and for watersheds of 29 to 17,540 acres. *Hazen* [1930] curves were drawn for the six time periods on each of the seven watersheds. Recurrence values for five years were determined for each curve. Multiple linear regression using log area and log duration as independent variables was then used to smooth the estimates. Results are shown in Figure 9. The analysis showed that the small 29-acre watershed behaved differently than the six larger watersheds and it was omitted from the regression analysis. The original Hazen values for this small watershed are shown in Figure 9 for comparison.

Minimum five-day water yield—In some cases, plans may be developed for pumping water from the stream to meet various needs. Minimum stream-flow data for periods shorter than one

TABLE 3 – *Mean daily stream flow (cfs), minimum for five-day period from watersheds of 920 to 17,540 acres in size, 1938–55*

Year	17,540 acres			4581 acres			2569 acres			920 acres		
	June	July	August	June	July	August	June	July	August	June	July	August
1938	4.1	1.6	1.3	1.05	0.35	0.14	...	...	...	...	...	...
1939	1.9	5.2	0.5	0.66	1.26	0.06	0.21	0.64	0.02	0.10	0.11	0.003
1940	38.0	6.2	1.5	4.37	1.07	0.28	2.37	0.56	0.15	1.18	0.17	0.07
1941	6.1	4.3	1.3	1.16	1.41	0.25	0.76	0.60	0.12	0.48	0.19	0.05
1942	13.0	2.3	1.0	2.16	0.38	0.18	0.89	0.24	0.08	...	...	...
1943	4.4	2.6	1.7	1.05	0.54	0.29	0.52	0.13	0.11	...	...	...
1944	1.3	0.2	0.1	0.26	0.01	0.01	0.15	0.002	0	0.07	0.002	0
1945	6.2	1.5	0.2	1.32	0.14	0.01	0.93	0.10	0.002	0.41	0.05	0.002
1946	11.0	9.4	3.4	2.36	1.65	0.25	1.42	1.12	0.21	0.59	0.51	0.09
1947	8.7	4.3	2.3	1.63	0.94	0.42	1.14	0.59	0.13	0.47	0.36	0.07
1948	4.1	1.3	0.2	0.95	0.25	0.02	0.51	0.13	0.001	0.16	0.04	0
1949	1.8	1.4	0.6	0.19	0.08	0.03	0.09	0.03	0.004	0.03	0.03	0
1950	4.5	2.2	0.3	0.80	0.30	0.05	0.22	0.08	0	0.19	0.05	0
1951	2.7	2.0	0.2	0.53	0.40	0.007	0.37	0.14	0	0.15	0.04	0
1952	1.9	1.4	0.3	0.29	0.15	0.009	0.13	0.05	0	0.06	0.04	0.005
1953	1.6	1.0	0.1	0.12	0.03	0.005	0.06	0.03	0	0.04	0.024	0
1954	0.6	0.1	0.3	0.054	0.003	0.007	0.03	0	0	0.01	0	0.001
1955	0.8	0.3	0.3	0.06	0.004	0.005	0.05	0	0	0.01	0	0.001

month would then be necessary in the proper planning for such use. Minimum five-day stream flow values for June, July, and August were compiled for the Coshocton watersheds to provide runoff data for short periods. These data for four different sized watersheds appear in Table 3. Minimum values for June range from 0.6 cubic feet per second for the largest watershed down to 0.01 cubic feet per second for the smallest. July and August values are even lower. These data show how critically dry the past few years have been.

Discussion—Records of runoff from small agricultural watersheds like those at Coshocton are noticeably lacking both in spread of coverage over the country and in length of record. The present and near-future needs for minimum water-yield evaluations from small areas demand the maximum use of all the available data.

Results of studies of data from the Coshocton watersheds presented show how the short-term yearly records of runoff were related to precipitation so as to make use of a 46-year Weather Bureau precipitation record for deriving estimates of minimum water yield for various frequencies. Minimum runoff values in this area increase with size of watershed. In physiographic provinces other than this, like some Arizona areas, the effect of watershed size may have exactly the opposite effect.

Monthly and seasonal values of minimum runoff are presented to show their variation between length of period and watershed size. These studies also show how data from watersheds of different sizes were used in the development of a water-yield and size relationship. It is believed that the water-yield and frequency results from a single watershed were improved in accuracy when they were used with similar data from other sized watersheds at Coshocton in developing a multiple-regression equation of minimum water yield for watershed sizes and length of period.

Seasonal occurrence of periods of minimum flow has usually been in late summer and early fall. Monthly values of these flows show how seriously low have been the water yields for recent years. This may serve as a good basis on which to design water-use programs, minimum water-yield values not likely to recur or be surpassed only on extremely rare occasions. This is evident from the fact that the total two-year precipitation, 1953–54, was the lowest in 46 years of record. Only once in this period was there a period nearly as dry: that in 1930–31 having about seven inches more rain than that in 1953–54.

Minimum five-day average stream flow for June, July, and August for this recent drought period was also extremely low. On the basis of these values one can calculate the extent of safe development for water use without storage.

It is not possible to present in this paper all of the reasons for variations in minimum water yield as found in this study. Neither does space provide for the inclusion of the many hydrologic evaluations made possible from this source of data. Several more papers are needed to do that job.

This paper is intended to stimulate the thinking in the field of upstream water problems, to encourage the use of every piece of available data for maximum use, and to emphasize the need for more data of this kind, both in increased length of records at present sites and at sites in other physiographic provinces.

Acknowledgment—This watershed-hydrology research project is maintained by the Agricultural Research Service, U. S. Department of Agriculture in cooperation with the Ohio Agricultural Experiment Station, Wooster, Ohio.

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Evaporation Study at Silver Lake in the Mojave Desert, California

HARRY F. BLANEY

Abstract—Silver Lake is located in the Mojave Desert north of Baker, California. It was formed within a period of three days as a result of a flood in the Mojave River in March 1938. Previously the lake had been dry for several years. Its maximum size was seven miles long and three miles wide. After this flood, daily observations were made of temperature, humidity, wind movement, precipitation, and pan evaporation at a Class A Weather Bureau evaporation station established adjacent to the lake, and of changes in water level and temperatures of the lake from May 1938 to April 1939. This paper presents a summary of these measurements. No inflow or outflow occurred during the study and the lake was entirely dry at the end of the following year. Borings in the tight clay lake bottom indicated there were no losses by seepage.

The purpose of the study was to determine coefficients for converting pan evaporation to lake evaporation and to develop an empirical relation between evaporation and meteorological factors, under desert conditions. The results show that annual evaporation from Silver Lake was about 79 inches for the period of observation, and that a coefficient of 0.60 could be used in reducing Weather Bureau pan evaporation to lake evaporation in desert areas with similar climate.

Introduction—Silver Lake is located several miles north of Baker in the Mojave Desert section of San Bernardino County, California. While this playa is usually dry, in years of high precipitation in the San Bernardino Mountains floods in the Mojave River sometimes fill it to depths of several feet. Following a flood in 1916, Silver Lake was ten feet deep but gradually became dry through evaporation after 18 months. In March 1938 following a storm in the mountains, flood waters of the Mojave River again filled the lake to a maximum depth of seven feet with water surface areas seven miles in length by three miles in width. By September 1939 most of the water in the lake had evaporated.

Silver Lake is the remnant of an ancient lake, known as Lake Mojave, that formerly covered 75 to 100 sq mi of the lower Mojave River basin. In recent times the principal material deposited in the lake bed by intermittent floods has been a fine silt or clay. The bed of Silver Lake shows unmistakable evidence of imperviousness. Figure 1 is a photograph of the dried lake-bed silt deposits in 1939. Test holes three feet deep failed to penetrate through the sediments which when dry opened in wide irregular cracks as shown in Figure 1. A well drilled on the eastern shore in 1939 showed tight material to a depth of 40 ft.

Formation of the lake presented an excellent opportunity to study the relation of evaporation from a standard Weather Bureau evaporation pan to the evaporation from a shallow lake under the unusual conditions of an essentially impervious lake bottom, low rainfall and high desert temperatures. Of particular advantage was the absence of inflow or outflow with negligible seepage, a condition resulting in evaporation being the sole means of water disposal.

Early in May 1938, a Class A evaporation station was established on the beach at the north end of the Lake and a gage was installed off shore for measuring changes in lake levels, by the Research Division of Irrigation, U. S. Soil Conservation Service [*Young* and *Blaney*, 1941], in cooperation with the City of Los Angeles, Department of Water and Power. Members of the Silver Lake power sub-station staff made the necessary daily observations at the lake.

Equipment—A standard Weather Bureau pan, a four-cup anemometer, and a standard rain gage, with a hygrothermograph and a thermometer in an instrument shelter, were installed at the evaporation station. The station was fenced to prevent interference by unauthorized persons and to keep out animals.

A small pier extending into the Lake to the maximum water depth was built near the station for the purpose of installing a gage for measuring changes in water surface elevations and a water thermograph for recording lake temperatures.

Results—Daily observations were made at 08 h 00 m of temperatures of air and of water in the evaporation pan and in the Lake, relative humidity, wind movement and water level in the Lake. Examples of daily maximum and minimum air and lake temperatures and humidity for the months of August and January are shown in Table 1. Records of daily and weekly evaporation from the

FIG. 1 – Dried silt deposits on the bottom of Silver Lake

Weather Bureau pan and wind movement for August and January are shown in Table 2.

Discussion—The data shown in Tables 1 and 2 illustrate the variation in observations during the summer and winter months. Table 3 presents a summary of monthly evaporation and meteorological records at Silver Lake for period May 1938 to April 1939 inclusive. The relation of monthly lake evaporation to monthly pan evaporation, air temperature, humidity, and wind velocity is shown in Figure 2.

Temperature—The Silver Lake district is a typical desert area with the usual high desert temperatures, shown in Tables 1 and 3 and Figure 2. The maximum recorded for the station during the summer of 1938 was 117° F. The mean maximum monthly temperature was 105° for July and August and 101° for September. Lowest temperature was 30° in November. Temperatures recorded in the shelter did not necessarily agree with those at the ground surface. In September surface soil temperatures were 15 to 25° warmer than air in the shelter or water in the evaporation pan.

TABLE 1 – *Daily maximum and minimum air temperatures, water temperatures, and humidity for August and January, Silver Lake, California*

Date	Temperature								Relative humidity			
	Air				Lake water							
	Aug. 1938		Jan. 1939		Aug. 1938		Jan. 1939		Aug. 1938		Jan. 1939	
	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.
	°F	°F	°F	°F	°F	°F	°F	°F	pct	pct	pct	pct
1	117	90	55	37	...	...	52	44	73	36	100	53
2	113	79	54	40	...	...	49	45	73	37	96	49
3	112	84	56	38	...	...	50	43	77	34	99	46
4	102	86	56	38	...	...	51	43	88	50	100	40
5	96	86	60	45	...	...	52	46	86	56	100	57
6	105	86	56	44	...	...	51	45	90	50	98	42
7	102	86	60	43	...	...	48	41	82	58	97	31
8	99	85	60	40	...	...	51	43	82	44	96	34
9	104	76	57	44	94	78	47	43	72	31	92	34
10	110	80	59	40	98	80	47	40	72	36	68	30
11	114	84	61	42	98	82	49	41	71	35	89	34
12	105	84	61	37	92	82	52	43	73	39	100	35
13	100	82	61	38	82	73	52	44	60	37	100	31
14	102	74	62	37	88	71	53	43	70	36	100	29
15	94	73	56	37	83	71	50	43	73	39	94	44
16	100	72	57	37	91	74	51	41	79	42	84	22
17	98	71	56	34	99	79	49	42	75	46	80	28
18	96	76	60	34	90	78	52	43	76	46	92	34
19	101	74	62	36	86	76	50	43	74	40	96	34
20	110	74	52	46	90	74	49	47	70	36	88	52
21	112	85	52	46	100	80	49	47	77	43	100	64
22	107	83	53	46	98	82	53	42	82	46	100	66
23	108	83	61	41	96	82	55	47	74	42	97	34
24	102	82	59	39	95	81	52	44	86	49	67	27
25	105	84	62	38	100	81	51	41	81	47	94	26
26	109	81	56	37	97	82	52	42	88	38	99	49
27	108	85	64	44	100	80	53	46	82	46	82	32
28	105	85	63	41	96	82	53	46	84	50	86	20
29	110	86	54	40	100	71	51	43	80	44	82	44
30	100	80	57	44	89	70	51	44	77	48	80	48
31	105	76	52	41	91	76	51	41	80	46	68	36
Mean	105	81	58	40	94	78	51	43	78	43	91	39

TABLE 2 – *Daily evaporation and wind movement for August and January, Silver Lake, California*

Date	Evaporation, Weather Bureau pan				Wind movement			
	Aug. 1938		Jan. 1939		Aug. 1938		Jan. 1939	
	Day	Week	Day	Week	Day	Week	Day	Week
	inch		inch		mi		mi	
1	0.708		0.048		140		79	
2	0.804		0.060		190		36	
3	0.780		0.084		163		160	
4	0.504		0.048		147		85	
5	0.372		0.040		137		85	
6	0.492	4.200	0.144		121	983	285	
7	0.408		0.180	0.604	127		161	891
8	0.708		0.118		188		170	
9	0.528		0.204		120		230	
10	0.528		0.156		101		179	
11	0.564		0.132		117		100	
12	0.660		0.072		152		62	
13	0.840	4.236	0.108		265	1070	96	
14	0.612		0.108	0.898	120		82	919
15	0.492		0.072		167		123	
16	0.492		0.228		105		163	
17	0.576		0.096		154		62	
18	0.552		0.084		126		59	
19	0.492		0.096		77		68	
20	0.528	3.744	...		98	847		
21	0.674		0.148[a]	0.724	141		255[a]	730
22	0.516		0.012		115		145	
23	0.612		0.132		153		80	
24	0.336		0.168		93		184	
25	0.444		0.108		83		82	
26	0.564		0.096		130		94	
27	0.504	3.650	0.144		97	812	183	
28	0.624		0.240		96		144	912
29	0.384		0.108		170		152	
30	0.408		0.180		136		255	
31	0.432		0.192		30		251	
Total.....	17.138		3.606		4059		4110	

[a] Amount for two days.

Relative humidity—Relative humidity as shown in Tables 1 and 3 and Figure 2 was less than in coastal regions where opportunity for moisture in the air is greater than the desert affords. Relative humidity at the evaporation station on the north lake shore was less when winds blew from the desert than when they first passed over the Lake. As the prevailing wind direction was from the south, off the lake, the amount of moisture in the air recorded at the evaporation station was greater than the usual desert humidity.

Wind movement—As a rule, the winds were not severe, as indicated in Tables 2 and 3 and Figure 2. They were, however, more continuous and of greater intensity than winds usually recorded in settled farming communities in Southern California. As a rule, the lake surface was more or less disturbed, sometimes to the extent of running small white-caps. Winds from the north were usually stronger than from the south, sometimes creating a peculiar condition. The water was deepest at the north end of the lake and gradually grew shallower toward the southern shore. On three occasions during the winter the intensity of the north wind was sufficient to force the water over dryland above the normal shore line at the south end of the Lake for short periods. The hourly average rate ranged from a minimum of 4.06 mi/hr in December 1938, to a maximum of 8.06 mi/hr in February 1939.

Evaporation—High desert temperatures, high rates of wind movement, and low humidity percentages were conducive to high rates of evaporation (Tables 2 and 3 and Figure 2). During the period of observation the maximum monthly evaporation of 19.75 inches from the Weather Bureau pan occurred in July 1938. Maximum evaporation from the Weather Bureau pan for a single day was 1.01 inches when maximum air temperature was 109°, wind movement was 220 miles in 24 hours and mean humidity 54 pct.

TABLE 3 – *Summary of evaporation and meteorological records at Silver Lake, California, May 1938–April 1939*

Year and month	Evaporation		Air temperature			Lake temperature			Humidity			Wind at Weather Bureau pan	Rainfall
	U. S. Weather Bureau pan	Silver Lake	Maximum	Minimum	Mean	Maximum	Minimum	Mean	Maximum	Minimum	Mean		
	Inch	Inch	°F	°F	°F	°F	°F	°F	Pct	Pct	Pct	mi/hr	Inch
1938													
May[a]	16.26	9.81	92	67	80	...	...	...	...	...	...	6.82	0.01
June	17.56	10.30	98	72	85[b]	88[b]	75[b]	82	70	36	53	7.10	0.46
July	19.75	10.33	105	80	92[b]	87[b]	75[b]	81	75	39	57	6.95	0.01
August	17.14	9.89	105	81	93[b]	94[b]	78[b]	86	78	43	60	5.46	0.05
September	12.88	7.59	101	74	88	89	74	82	81	45	63	4.39	0.03
October	7.80	5.68	80	56	68	72	61	66	78	39	58	4.87	0.16
November	6.06	3.84	64	38	51	53	44	49	66	29	48	5.23	0.00
December	3.23	2.21	62	42	52	53	45	49	90	42	66	4.06	1.60
1939													
January	3.61	2.37	58	40	49	51	43	47	91	39	65	5.52	1.17
February	6.15	4.68	57	37	47	51	40	45	75	32	54	8.06	0.12
March	8.38	5.70	72	48	60	...	...	...	80	34	57	6.41	0.30
April	11.76	7.06[c]	84	55	69	...	...	...	71	26	48	5.93	0.32
Total	130.58	79.46	...	...	...	...	...	...	...	...	...	...	3.90
Average	...	...	81	58	70	...	...	...	78	37	57	5.90	...

[a] May 1 to 12 estimated.
[b] Not a complete month.
[c] Estimated from pan evaporation.

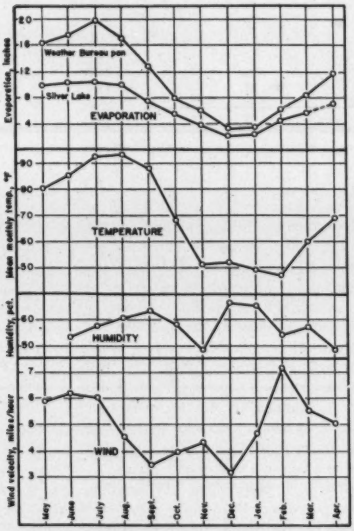

FIG. 2 – Monthly evaporation and meteorological data, Silver Lake, California

The ratio of annual lake evaporation of 79.46 inches to annual Weather Bureau pan evaporation of 130.58 inches shown in Table 3 is 0.61. Other studies indicate that the coefficients for reducing Weather Bureau pan evaporation to lake evaporation range from 0.60 for arid conditions to 0.80 for humid areas [*American Society of Civil Engineers*, 1934]. The results of the Silver Lake study confirm the fact that a reduction coefficient of 0.60 may be used when estimating evaporation from lakes or reservoirs in desert areas from pan records. Adjustment of pan evaporation, for water temperature and wind movement, has been suggested by *Kohler*, *Nordenson*, and *Fox* [1955].

Empirical formulas—In connection with the Pecos River Joint Investigation, *Blaney* and *Morin* [1942] developed empirical formulas for computing evaporation and consumptive use in areas where temperature and humidity data are available and no pan measurements have been made. An analysis of the relation between monthly temperature, humidity, evaporation and per cent of daytime hours lead to the empirical formula: $e = k_e\,(114 - h) = k_e c$, in which e = monthly evaporation in inches; k_e = monthly coefficient; $f = t \times p/100$ = monthly use factor where t = mean monthly temperature F° and p = monthly per cent of daytime hours; h = average per cent relative humidity; and $c = f\,(114 - h)$ = monthly

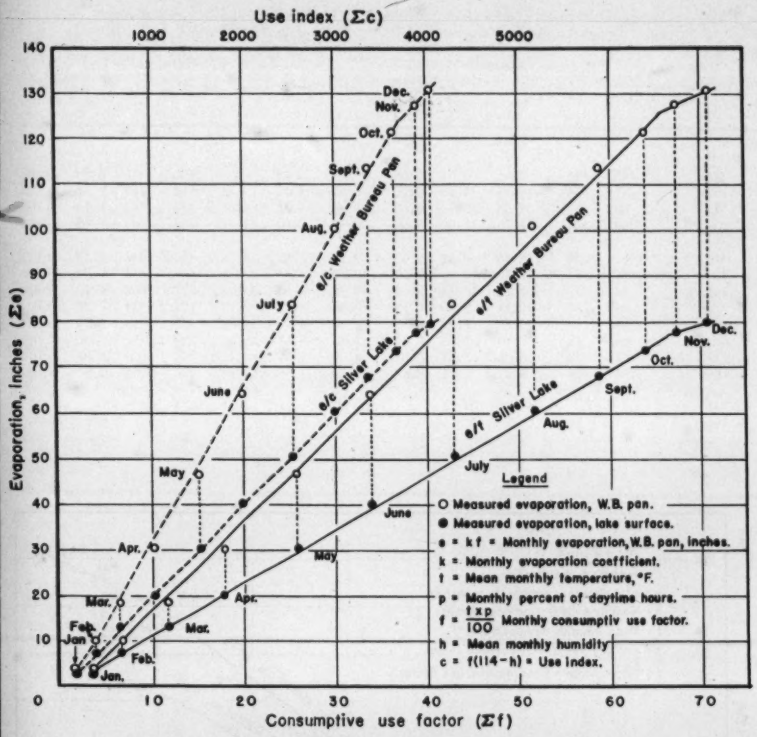

FIG. 3 – Relation between observed accumulative monthly evaporation from Weather Bureau pan and lake surface and meteorological data, Silver Lake, California, 1938–39

use index. Later in areas where average humidity was not available this equation was revised by *Blaney* and *Criddle* [1950] to $e = k_1 f$ = monthly evaporation in inches, where $k_1 = e/f$ = monthly empirical coefficient.

Table 4 illustrates how observed data at Silver Lake can be used to compute coefficients k_c and k_f for estimating evaporation in other desert areas. Data given in Table 4 are plotted in Figure 3 after procedure developed by *Blaney* and *Morin* [1942]. Figure 3 shows the relation between accumulative monthly evaporation from pan and lake and accumulative use factor f and use index c at Silver Lake. The relation between use factor f and evaporation at Bard and Lake Elsinore, California, is illustrated in Figure 4. These figures indicate the straight line relationship which exists for most of the year for the two empirical formulas. The procedure indicates how annual evaporation may be estimated when a few monthly measurements are missing, but monthly temperature and humidity are available for the entire year [*Blaney*, 1956].

The results of evaporation investigations by the Agricultural Research Service, U. S. Department of Agriculture, in cooperation with the State Engineer of California, in other parts of California, have been published in a report by *Blaney* and *Corey* [1955].

TABLE 4 – *Empirical coefficients for estimating evaporation from lakes or reservoirs in arid areas along with observations of evaporation and meteorologic data upon which they are based, 1938–1939, Silver Lake, California*

Year and month	Mean		Evaporation		Ratio	Daytime hours	Lake evaporation					
	Temp. t	Humidity h	W.B. pan e_p	Lake Σe	e/e_p	p	Factor f	Σf	Index c	Σc	kf	k_c
	°F	pct	inch	inch		pct						
1939												
Jan.	49	65	3.61	2.37	0.66	7.02	3.44	0	169	0	0.69	0.014
Feb.	47	54	6.15	4.68	0.76	6.87	3.23	3.44	194	169	1.45	0.024
Mar.	60	57	8.38	5.70	0.68	8.35	5.01	6.67	286	363	1.14	0.020
Apr.	69	48	11.76	7.06	0.60	8.85	6.10	11.68	403	649	1.16	0.018
1938												
May	80[a]	50	16.26	9.81	0.60	9.79	7.83	17.78	462	1052	1.25	0.021
June	85	53	17.56	10.30	0.59	9.80	8.33	25.61	508	1514	1.24	0.020
July	92	57	19.75	10.33	0.52	9.96	9.16	33.94	522	2002	1.13	0.020
Aug.	93	60	17.14	9.89	0.58	9.38	8.72	43.10	471	2544	1.13	0.021
Sept.	88	63	12.88	7.59	0.59	8.36	6.99	51.82	356	3015	1.09	0.021
Oct.	68	58	7.80	5.68	0.73	7.86	5.34	58.81	299	3371	1.06	0.019
Nov.	51	48	6.06	3.84	0.63	6.94	3.54	64.15	234	3670	1.08	0.016
Dec.	52	66	3.23	2.21	0.68	6.82	3.55	67.69	170	3904	0.62	0.013
Total	...	...	130.58	79.46	...	100.00	71.24	71.24	4074	4074	...	...
Average	70	57	...	...	0.61	...	...	...	...	...	1.12	0.019

[a] Estimated.

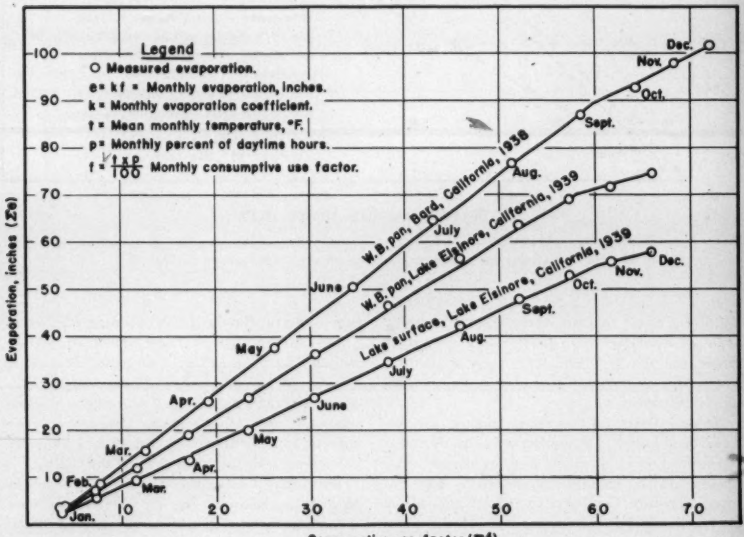

FIG. 4 – Relation between accumulative monthly evaporation and meteorologic data at Bard and Lake Elsinore, California

Acknowledgments—The author desires to acknowledge that the study set forth in this paper was planned jointly with the late Arthur A. Young who prepared an office report and Donald McCord Baker, Consulting Engineer, Los Angeles. The cooperation of the Department of Water and Power of the City of Los Angeles and the careful daily observations for more than a year of Messrs. Curtis, Pace, and West of the Silver Lake Sub-Station staff of the Department is gratefully acknowledged.

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Rainfall-Runoff Relation for Small Basins

J. F. Miller and J. L. H. Paulhus

Abstract—Procedures for computing storm runoff from rainfall for other than very small basins have been in use for many years. A rainfall-runoff relation for a basin of 4.1 sq mi is derived and is found to be applicable to other small basins.

Introduction—For any basin in which the time interval between rainfall peak and flood crest is less than about six hours, there is insufficient time for the collection of reports and the preparation and effective dissemination of stream-flow forecasts. Consequently, stage forecasts are seldom provided for such basins, and few attempts have been made to derive applicable rainfall-runoff relations.

During the course of a research project it became necessary to establish a record of storm runoff from rainfall records. It was quickly established that the type of rainfall-runoff relations for large basins was not adaptable to small ones, and that a new type was required.

Deriving the relation—The basic data requirements for deriving a rainfall-runoff relation are concurrent stream-flow and rainfall records for at least several years. An additional requirement for the small basin is that the rainfall record must be from a recording gage. A thorough search of the records for small basins in the eastern United States led to the choice of the Little Falls Branch near Bethesda, Maryland, with an area of 4.1 sq mi, having concurrent stream-flow and recording rain-gage records since water year 1946.

In the ordinary rainfall-runoff relation as described by *Kohler* and *Linsley* [1951], the four independent parameters are: antecedent precipitation index, season or week of year, storm duration, and storm rainfall. For very small basins intense rainfalls for short durations are extremely critical in determining peak discharges, suggesting that rainfall for relatively short intervals should be substituted for the parameters, duration and magnitude of storm rainfall. While shorter intervals might be better suited for very small basins, hourly increments of rainfall were tried because they are readily available in the *Hydrologic Bulletin* and *Climatological Data*. More critical hourly rainfall values can be obtained from the gage record itself, but the analysis of the recorder charts is a tedious task, and the limitations of the procedure are such that the substitution of clock-hour rainfall data as published did not seriously hamper the development of the procedure nor greatly affect its accuracy.

As in the case of rainfall-runoff relations for large basins, the antecedent precipitation index API was computed for the time of beginning of the rainfall period, that is, for the beginning of each hour of rainfall. For example, assuming an API of 1.37 on the day preceding the hypothetical rainstorm in column 3 of Table 1, the initial API for each hour of rainfall are as shown in column 5.

The API for the first hour of rainfall is 1.37 as computed in the ordinary manner [*Kohler* and *Linsley*, 1951; *Linsley*, *Kohler*, and *Paulhus*, 1949, pp. 414–417] through midnight of the day preceding the storm. The API for the second hour is 1.37 plus the rainfall for the first hour, 0.08 inch, making the API for the second hour 1.45. The API for successive hours is computed in the same fashion. Since the relation was based on this interpretation of API, it will not yield reliable estimates of runoff unless the API is computed in this manner.

Experience has shown that the seasonal factor in rainfall-runoff relations undergoes little change within a physiographically homogeneous region. Since Little Falls Branch is in the same region as the Monocacy River, the seasonal curves derived by *Kohler* and *Linsley* [1951] for the Monocacy River at Jug Bridge, Maryland, area 817 sq mi, are used without modification in the Little Falls Branch relation of Figure 1.

Since analysis of the storm hydrograph yields only total storm runoff, some distribution of hourly increments of runoff must be made to derive

TABLE 1 – *Data for deriving rainfall-runoff curves of Figure 1*

Time		Rainfall		API	Total runoff		Runoff rate
From 1	To 2	Increment 3	Total 4	5	First approx. 6	Adjusted 7	8
h	h	inch	inch		inch	inch	in/hr
01	02	0.08	0.08	1.37	0	0	0
02	03	0.10	0.18	1.45	0	0	0
03	04	0.37	0.55	1.55	0.02	0.02	0.02
04	05	0.35	0.90	1.92	0.17	0.14	0.12
05	06	0.21	1.11	2.27	0.26	0.22	0.08
06	07	0.34	1.45	2.48	0.43	0.36	0.14
07	08	0.03	1.48	2.82	0.43	0.36	0

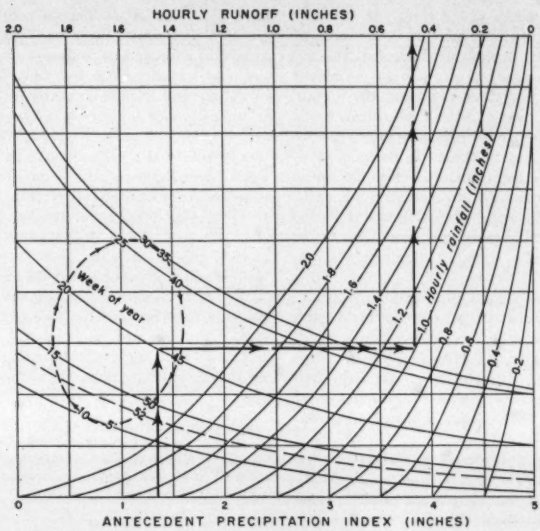
HOURLY RUNOFF (INCHES)
2.0 1.8 1.6 1.4 1.2 1.0 0.8 0.6 0.4 0.2 0
Hourly rainfall (inches)
Week of year
ANTECEDENT PRECIPITATION INDEX (INCHES)
0 1 2 3 4 5

FIG. 1 – Rainfall-runoff relation for Little Falls Branch near Bethesda, Md., area 4.1 sq mi

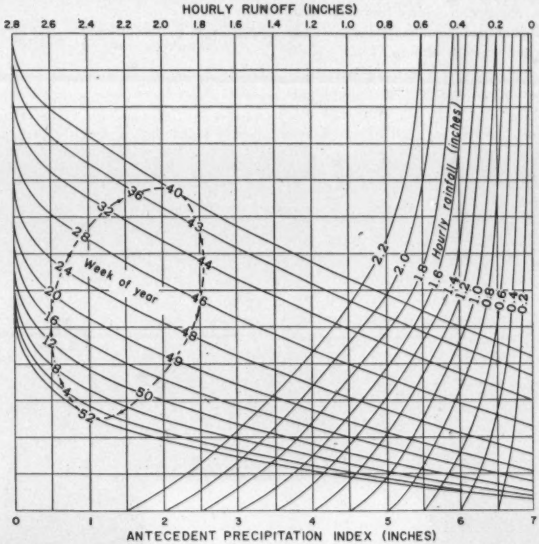
HOURLY RUNOFF (INCHES)
2.8 2.6 2.4 2.2 2.0 1.8 1.6 1.4 1.2 1.0 0.8 0.6 0.4 0.2 0
Hourly rainfall (inches)
Week of year
ANTECEDENT PRECIPITATION INDEX (INCHES)
0 1 2 3 4 5 6 7

FIG. 2 – Rainfall-runoff relation for Ralston Creek at Iowa City, Iowa, area 3.01 sq mi

the rainfall-runoff curves of Figure 1. As a first approximation, the distribution was estimated by using an ordinary rainfall-runoff relation. This was done by entering the relation with the initial API (1.37 in the case of the hypothetical storm), proceeding to the proper duration curve, thence to the runoff value for the accumulated rainfall as indicated by the rainfall curves. In the example of Table 1, the first approximation of runoff distribution shown in column 6 was obtained by entering the basic relation with the initial API, 1.37, the proper week of the year, then proceeding to the proper duration and accumulated rainfall as shown in column 4.

The total accumulated runoff (column 6) is 0.43 inch. Assuming that the stream-flow hydrograph for this hypothetical storm yields 0.36 inch runoff, the accumulated runoff values of column 6 are adjusted by the ratio 0.36/0.43 to obtain the values of column 7. Column 8 shows the incremental hourly runoff for the adjusted accumulation of column 7.

The next step in the derivation was to enter the weekly curves of Figure 1 with the proper hourly API and week of year and plot the resulting value against the corresponding runoff of column 8, labeling each point with the corresponding hourly rainfall of column 3.

After a large number of storms had been thus plotted, first-approximation rainfall curves were drawn. The second approximation of hourly basin unoff was obtained from this first-approximation elation, the points replotted and second-approximation rainfall curves drawn. The third approximation of hourly runoff was similarly obtained from the second-approximation relation to yield the third-approximation curves, with no further significant improvement indicated.

Use of relation—Since the rainfall-runoff relation of Figure 1 is based on hourly API and hourly rainfall, it yields satisfactory estimates of runoff only if these parameters are used. While the relation was derived specifically for the Little Falls Branch near Bethesda, Maryland, area 4.1 sq mi, it has been used satisfactorily on basins from two to 15 sq mi, some being as far away as North Carolina. All basins were in a physiographically homogeneous region extending from New Jersey to Georgia and it is possible that the relation would be applicable to most small basins in this region. However, there is a limit to its geographic range of applicability because a similar relation (Figure 2) derived for Ralston Creek at Iowa City, Iowa, area 3.01 sq mi, was not applicable to the Little Falls Branch.

Acknowledgments—M. A. Kohler, Chief Research Hydrologist for the U. S. Weather Bureau, conceived the idea of this new type rainfall-runoff relation, and he and T. J. Nordenson made several suggestions concerning the procedure during the course of its development.

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Soviet Methods of Reporting and Displaying Results of Chemical Analyses of Natural Waters and Methods of Recognizing Oil-Field Waters: A Summary

GEORGE V. CHILINGAR

Abstract—Several Soviet methods of reporting and displaying results of chemical analyses of natural waters are briefly outlined. In addition, some methods of studying waters from petroliferous formations are presented. A certain relationship may exist between the chemical composition of oil-field waters and the stratigraphic depth. The relationship between the total mineralization and the chemical composition of waters from the same stratum can be clearly shown graphically.

Some Soviet methods of reporting and displaying results of water analyses—In the USSR, Kurlov's formula is commonly used in showing the chemical composition of natural waters. The composition of water is presented as a fraction: the per cent equivalent (pct equ) r of anions is recorded in the numerator, whereas the pct equ of cations is presented in the denominator, in the order of abundance. Ions having a concentration below five pct equ, however, are not recorded. In the *Alekin's* [1953, p. 111] version of Kurlov's formula, the total of all equivalents is taken as 100 pct, with anions and cations each totalling 50 pct. The amount of total mineralization M, in g/kg, is placed in front of the fraction. Undissociated components and gases, which impart characteristic properties to the natural waters, are also placed here (CO_2 or H_2S in mg/l, radioactivity, etc.). The temperature t and the yield D, on the other hand, are recorded after the fraction. For example, the chemical composition of the Aleksandro-Ermolovskiy spring in Pyatigorsk, USSR, can be presented in the following manner (*Alekin*, 1953, p. 111)

$$[CO^2_{1.0}\,H^2S_{0.01}]M_8\,\frac{rCl_{20}rHCO^3{}_{18}rSO^4{}_{11}}{rNa_{30}rCa_{15}}\,t_{45}{}^{\circ}D5660$$

Although not mentioned by Alekin, in the USSR the debit D is most commonly expressed in m^3/day. Other versions of the Kurlov's formula are also used in USSR (M.-A. Kashkay, personal communication).

N. I. Tolstikhin's graph is widely used in the USSR for the purpose of comparing the chemical composition of different waters and establishing their genetic relationships (Fig. 1). The sides of Tolstikhin's square are divided into 50 equal parts (50 pct equ). The Na + K content in pct equ is plotted on the upper side, whereas the Ca + Mg content is shown on the lower side. The HCO_3 + CO_3 and SO_4 + Cl contents are plotted on the left and right sides, respectively. The points representing genetically related waters, having similar chemical composition, fall close to each other and form natural groups. The main shortcoming of this method, however, is the combining of Ca with Mg and Cl with SO_4 ions, which prevents determination of the role and significance of the individual constituent ions.

Tolstikhin also proposed a graph for numbering the natural waters on the basis of chemical composition (Fig. 2). The sums of mg-equ of cations and anions are taken as 100 pct each instead of 50 pct as in the two previous systems. Obviously, on using this graph the most highly mineralized waters will have large numbers (88, 89, 98, 99, 100).

Methods of recognizing oil-field waters—The study of oil-field brines shows that their composition does not remain constant throughout any particular bed. For example, the samples of water from Apsheron peninsula, taken from the oil-water contact at the beginning of exploitation, have higher mineralization than the water samples obtained from the bore-holes outside the productive limits (producing 100 pct water). As exploitation progresses, the mineralization drops because of the edge water encroachment [*Agadzhanov*, 1954, p. 255].

The change in the composition of water, on going from the near-crest area toward the flanks, also depends on the type of water (hard or alkaline); and the greatest change occurs in alkaline waters [*Agadzhanov*, 1954, p. 255]. This change occurs mainly at the expense of Cl and Na + K contents. The ($HCO_3^{\prime}$ + CO_3 + H. K.) content, on the other hand, is subject to the least amount of fluctuation. (The meaning of H. K. is not clear; possibly, it is a general symbol for 'weak acids,' because K is the first letter in the Russian word

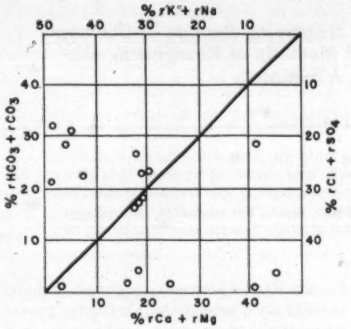

FIG. 1 – Tolstikhin's square [*Agadzhanov*, 1954, p. 251]

for acid. It could also mean 'naphthenic acids,' because 'naphthenic' starts with a Russian letter H.)

The relationship between the chemical composition of Apsheron peninsula waters and the stratigraphic depth is subject to the following rules. (1) The mineralization of water decreases with stratigraphic depth. (2) Cl, Ca, and Mg decrease with depth. (3) Na + K and ($HCO_3 + CO_3$ + H. K.) gradually increase with depth. (4) The transition from hard to alkaline waters occurs at maximum concentration, of not exceeding 0.1 g-equ per 100 g of water (5–6.5° Bé). As a rule, the waters are hard at concentrations above 0.1 g-equ. (5) The HCO_3 content (in equ) does not exceed the Cl content ($A_1 < S_1$). (6) Usually, the waters

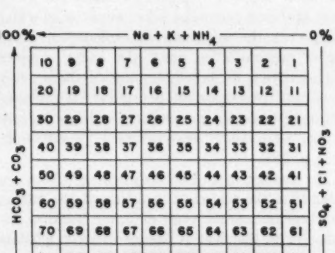

FIG. 2 – Tolstikhin's graph for numbering natural waters on the basis of chemical composition [*Alekin*, 1953, p. 113]

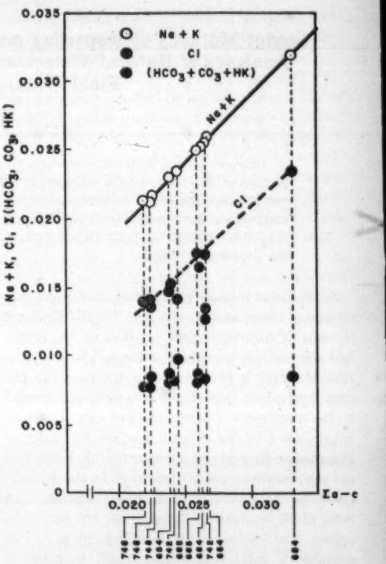

FIG. 3 – Relationship between the total mineralization (total of anions or cations) and the chemical composition of waters (all in g-equ, and same scale) from the bore-holes of one oil deposit in the southeastern Caucasus [*Agadzhanov*, 1954, p. 256]

do not contain SO_4 anion. If present, however, its concentration does not exceed 0.0004 g-equ per 100 g of water.

According to K. L. Malyarov [*Agadzhanov*, 1954, p. 256], the above rules, however, do not hold true in the Groznenskiy region.

The relationship between the total mineralization of water from the same stratum and the amount of various constituent ions can be clearly demonstrated graphically (Fig. 3). The total mineralization (Σ anions-cations) in g-equ is plotted on the abscissa, whereas the Cl, Na + K, and ($HCO_3 + CO_3$ + H. K.) contents are plotted on the ordinate. The total mineralization as used by Agadzhanov (Σa–c) means the total g-equ of cations or anions (Σa = Σc). As shown in Figure 3, the Cl and Na + K contents increase with increasing mineralization (straight line relationship). The ($HCO_3 + CO_3$ + H. K.) content (black circles), on the other hand, varies only very slightly.

Thus, it may be possible to determine whether

a water sample comes from a particular bed or represents a mixture of waters from different strata.

Conclusion—The problem of origin of the oilfield brines and determination of their point of influx requires systematic observations and statistical studies.

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Moisture Movement in Porous Materials under Temperature Gradients

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Abstract—A theory of moisture movement in porous materials under temperature gradients is developed which explains apparently discordant experimental information, including (a) the large value of the apparent vapor transfer, (b) effect of moisture content on net moisture transfer, and (c) the transfer of latent heat by distillation.

The previous simple theory of water vapor diffusion in porous media under temperature gradients neglected the interaction of vapor, liquid and solid phases, and the difference between average temperature gradient in the air-filled pores and in the soil as a whole. With these factors taken into account, an (admittedly approximate) analysis is developed which predicts orders of magnitude and general behavior in satisfactory agreement with the experimental facts.

An important implication of the present approach is that experimental methods used to distinguish between liquid and vapor transfer have not done so, since what has been supposed to be vapor transfer has actually been series-parallel flow through liquid 'islands' located in a vapor continuum.

Equations describing moisture and heat transfer in porous materials under combined moisture and temperature gradients are developed. Four moisture-dependent diffusivities arising in this connection are discussed briefly.

Introduction

In recent years there has been much interest in the physics of moisture movement in porous media under temperature gradients. Apart from its significance to such problems as those of heat and moisture transfer in building materials, (thermal) insulating materials and clothing, this question is of great importance in microhydrological and micrometeorological studies. The physical theory of many microhydrological phenomena which may be safely taken to be isothermal is well advanced [*Philip*, 1957b]; but analysis of such problems as the heat and moisture balance during evaporation from soils requires an understanding of the influence of temperature gradients on soil water movement.

To the present time an adequate physical explanation of the growing body of experimental data on this topic has not been provided. A number of mechanisms have been invoked to account for the facts, but have not led to a plausible explanation. In this communication we show that the facts which have provoked these speculations can be explained in terms of the classical mechanisms of vapor diffusion and liquid movement by capillarity.

The Facts to be Reconciled

The facts to be explained or reconciled may be grouped under four heads:

(a) *The large value of the apparent vapor transfer*—This aspect has received the most attention. Many workers either explicitly state or give data which imply that observed water vapor transport under temperature gradients greatly exceeds that predicted by the theory of vapor diffusion modified to take account both of the reduction of diffusion cross-section by the solid matrix and the liquid water and of the tortuosity of the diffusion path through the medium. Much of this work cannot be analyzed quantitatively, since either the boundary conditions are too complicated or else the data reported miss out one or more important determinants of the system. However, three groups have given quantitative comparisons between observed (presumed) vapor transfer and the predictions of the 'simple theory.' These comparisons are summarized in Table 1, to which are added the results of some further examinations of the data by the present authors.

(b) *Effect of moisture content on moisture transfer*—Many investigators [e.g. *Smith*, 1943; *Jones* and *Kohnke*, 1952; *Gurr* and others, 1952; *Hadley* and *Eisenstadt*, 1955] have observed that moisture transfer under temperature gradients is negligibly small both in very dry and in very wet media, but attains a fairly well-defined maximum at an intermediate moisture content which appears to depend both on the soil-water tension and on the air-filled porespace. Jones and Kohnke report this maximum as occurring at tensions ranging from 60 cm (sand) to 6000 cm (loam), corresponding to volumetric moisture contents (θ cm³ of liquid water/cm³) 0.031 to 0.105. Other data are in general agreement. Although the simple theory predicts a point of maxi-

TABLE 1 – *Experimental data on water-vapor transfer in soils under temperature gradients*

Authors	How movement identified as in vapor phase	Porosity $\theta + a$	Volumetric moisture content θ	Volumetric air content a	Ratio of observed transfer to value predicted by simple theory η	Remarks[b]
Gurr and others [1952]	Liquid flow assumed proportional to Cl movement (NaCl used as tracer)	0.472[a]	0.074	0.398[a]	3.6	Uncertainty in this value about 10%
Taylor and *Cavazza* [1954]	Gaps in column presumed to restrict movement to vapor phase	0.555[a]	0.206[a]	0.349	18	Recomputed by us (from Fig. 5 after one day).
		0.657[a]	0.158[a]	0.499	9.8	Computed by us (from Fig. 4 after 2 days).
Rollins and others [1954]	Liquid return flow (cold to hot) via external capillary presumed to equal vapor flow (hot to cold) in column	0.690	0.179	0.511	4.6	Computed by us (from Fig. 6)
		0.541	0.202	0.339	4.6	" " " (trial no. 7)
		0.521	0.260	0.261	5.7	" " " (from Fig. 7)
		0.503	0.288	0.215	6.0	Computed by Rollins and others (trial no. 1)
		0.452	0.303	0.149	6.8	Computed by us (from Fig. 8)
		0.407	0.329	0.078	9.8	" " " (from Fig. 9)

[a] These values computed on assumption that S.G. of soil material = 2.65.

[b] Figure numbers in this column refer to figures appearing in the corresponding paper cited in column 1.

mum vapor transfer, this is generally at much too low a moisture content to agree with observation.

(c) *The transfer of latent heat by distillation*—Investigations [*Krischer* and *Rohnalter*, 1940; *de Vries*, 1952ab] have shown that the mechanism of vapor diffusion accounts quite adequately for the contribution of heat transfer by distillation to the apparent thermal conductivity of porous materials. These investigations did not depend on detailed use of the 'simple theory.'

(d) *Effect of air pressure on apparent vapor transfer*—Molecular diffusion is proportional to the mean free path, which varies inversely with gas pressure. *Jennings* and others [1952] have confirmed this behavior qualitatively for moisture transfer under temperature gradients in soils, though their data are not amenable to quantitative analysis.

The situation is, then, that the experimental data of (a) and (b) do not conform to the simple vapor-diffusion theory, but that the aspects of the problem mentioned under (c) and (d) can be explained in terms of molecular diffusion. It is important to note that the application of molecular diffusion concepts to (c) and (d) does not involve the detailed application of the 'simple theory.'

THE SIMPLE THEORY OF VAPOR TRANSFER

We need to present this theory briefly before proceeding to our explanation of these matters. The equation of vapor diffusion, modified so as to apply in porous media [*Penman*, 1940; *Krischer* and *Rohnalter*, 1940; *van Bavel*, 1952; *Rollins* and *others*, 1954] may be written

$$q_{vap} = -D_{atm} \nu \alpha a \nabla \rho \qquad (1)$$

where q_{vap} is the vector vapor flux density, gm cm^{-2} sec^{-1}

D_{atm} is the molecular diffusivity of water vapor in air, cm^2 sec^{-1}

α is a tortuosity factor allowing for the extra path length

a is the volumetric air content of the medium (cm^3 of air/cm^3)

ρ is the density of water vapor, gm cm^{-3}

ν is the 'mass-flow factor' introduced to allow for the mass flow of vapor arising from the difference in boundary conditions governing the air and vapor components of the diffusion system.

Krischer and Rohnalter found that D_{atm} for diffusion due to a temperature gradient could be represented by the expression $4.42 \times 10^4 \, T^{2.3}/P$ in the range 20°–70°C, where T is the absolute temperature, °K, and P is the total gas pressure, mm Hg. Data for isothermal conditions [*Mache*, 1910; *Summerhays*, 1930; *Schirmer*, 1938] differ appreciably from this at temperatures above 40°C and there is scope for further investigation of water vapor diffusion under a temperature gradient. We use values of D_{atm} given by Krischer and Rohnal-

ter's relationship where numerical values are needed.

Stefan [see, for example, *Partington*, 1949, p. 912] showed that for steady diffusion in a closed system between an evaporating source and a condensing sink

$$\nu = P/(P - \hat{p}) \tag{2}$$

where $\hat{p}$ is the partial pressure of water vapor, mm Hg. It is by no means obvious that ν will assume this value under non-stationary conditions. However the order of magnitude of the deviation of ν from unity follows from (2); ν is clearly quite close to 1 at normal soil temperatures.

Extended Treatment of Vapor Transfer

In this section we show how (1) may be extended to give (a) a separation of the 'isothermal' and 'thermal' components of vapor transfer, and (b) the effect of relative humidity (or soil water pressure) on the transfer. It will be noted that these developments depend only on the proportionality of the vapor flux to the vapor-density gradient. This is retained in the revised theory presented later in the paper, so that these results (modified in the case of thermal transfer) are also relevant there.

We introduce the thermodynamic relationship [see *Edlefsen* and *Anderson*, 1943, p. 260]

$$\rho = \rho_0 h = \rho_0 \exp(\Psi g/RT) \tag{3}$$

where ρ_0 is the density of saturated water vapor, gm cm^{-3}

h is the relative humidity

g is the acceleration due to gravity, cm sec^{-2}

R ($= 4.615 \times 10^6$) is the gas constant of water vapor, erg gm^{-1} °C^{-1}

Ψ is the water pressure in cm in thermodynamic equilibrium with the water in the medium, with atmospheric pressure as datum; thus Ψ is negative in unsaturated media. It will be noted that Ψ depends on θ and on T. In this communication we take as negligible the influence of soluble salts in the water on h and Ψ (as here defined).

Hence

$$\nabla\rho = h\nabla\rho_0 + \rho_0\nabla h \tag{4}$$

Before proceeding, we must discuss the influence of temperature on h for a constant value of θ. The roles of physical adsorption and capillary condensation in determining the adsorption isotherm (and hence the $\Psi(\theta)$ relation) of a liquid in a porous material have been reviewed by *Carman* [1953]. At low values of h physical adsorption is dominant, while capillary condensation is the important process at high values of h. The data of *Carman* and *Raal* [1951] suggest that $h = 0.6$ is a suitable (though arbitrary) transition point. Here, then, we assume that $h(\theta)$ and $\Psi(\theta)$ are determined by physical adsorption for $h < 0.6$ and by capillarity for $h > 0.6$. Physical adsorption depends primarily on h, and for a fixed h, $-(1/\theta)(\partial\theta/\partial T)$ is somewhat less than the coefficient of thermal expansion of the free liquid [see, for example, *McBain*, 1932, p. 143]. From this it is easily checked that, for $h < 0.6$, $\partial h/\partial T = 0$ to a good approximation. On the other hand, capillarity depends on the surface tension, σ dyne cm^{-1}, so that in the region of capillary condensation Ψ is proportional to σ and $\partial\Psi/\partial T$ is equal to $(\Psi/\sigma)(d\sigma/dT)$. We use this value of $\partial\Psi/\partial T$ in the later developments. However, it will be found that, provided $h > 0.6$, the resulting temperature effect on h is so small that we may safely put $\partial h/\partial T = 0$. Therefore we may take $\partial h/\partial T = 0$ in the full range of h.

Reverting to (4), we see that ρ_0 is a function of T only and h is a function of θ only. Therefore (4) becomes

$$\nabla\rho = h\frac{d\rho_0}{dT}\nabla T + \rho_0\frac{dh}{d\theta}\nabla\theta \tag{5}$$

Using (3) to evaluate $dh/d\theta$, we obtain

$$\nabla\rho = h\frac{d\rho_0}{dT}\nabla T + \frac{g\rho}{RT}\frac{\partial\Psi}{\partial\theta}\nabla\theta \tag{6}$$

Putting (6) in (1), we get an equation of the form

$$q_{vap}\rho/\rho_w = -D_{T\,vap}\nabla T - D_{\theta\,vap}\nabla\theta \tag{7}$$

where ρ_w gm cm^{-3} is the density of (liquid) water. We have thus separated the flux into two components, that due to the temperature gradient and that due to the moisture gradient. The evaluation of the isothermal vapor diffusivity, $D_{\theta\,vap}$, has been given elsewhere [*Philip*, 1955] and need not detain us at this point. Our interest is in the thermal vapor diffusivity $D_{T\,vap}$ which, according to the preceding simple theory, is given by

$$D_{T\,vap} = D_{atm}\nu\alpha a h\beta/\rho_w \tag{8}$$

Here we have written β for $d\rho_0/dT$. β is, of course, temperature dependent, but we may reasonably adopt the constant value 1.05×10^{-6} gm cm^{-3} °C^{-1} as representative of the temperature range 10°C to 30°C, which will be typical for applications discussed in this paper.

As an illustrative example we have calculated D_{Tvap} (and the diffusivities D_{Tliq} and D_T to be defined later) for Yolo light clay on the basis of the $\Psi(\theta)$ and $K(\theta)$ relationships for this soil given by *Moore* [1939]. Further we have adopted the following values for constants occurring in (8): ¾ for α [*Penman*, 1940; *de Vries*, 1950b], 0.274 cm² sec⁻¹ for D_{atm} at 20°C [*Krischer* and *Rohnalter*, 1940], 1.73×10^{-4} gm cm⁻³ for ρ_0 at 20°C, 1.00 for ρ_w and 1.024 for ν at 20°C. The results are shown in Figure 1.

The original formulation of (1) by Penman was for the diffusion of CS_2 and CH_3COCH_3, neither of which, presumably, interacted with either the liquid or solid phases of the medium. Applications of this equation to water vapor by *Penman* and *Schofield* [1939], *de Vries* [1950a], *Gurr* and others, [1952], *Philip* [1953], *Taylor* and *Cavazza* [1954], *Rollins* and others [1954] have disregarded the interaction of the water vapor with the liquid and solid phases. We therefore remark at this stage that the failure of this theory of moisture transfer should occasion no surprise, and leave the question of how the theory is to be modified to a later point in this paper.

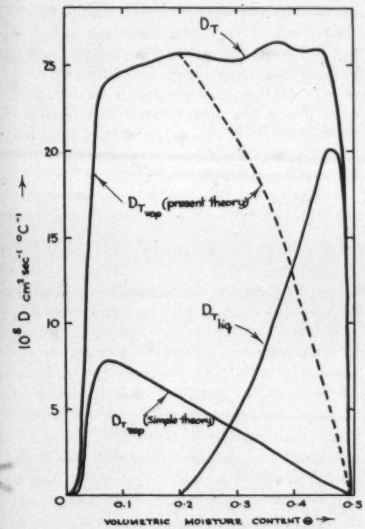

FIG. 1 – Thermal vapor diffusivity D_{Tvap}, both according to the simple theory and according to the present theory; thermal liquid diffusivity D_{Tliq}; thermal moisture diffusivity, D_T; all as functions of moisture content for Yolo light clay at 20°C

LIQUID TRANSFER

Liquid flow also enters into the general picture of soil-water phenomena involving temperature gradients. In this section we provide a general theory of liquid movement in porous media under temperature and moisture gradients. In the final section of the paper this is integrated with the approach to vapor transfer to provide a general theory of liquid and vapor transfer under temperature and moisture gradients.

Darcy's law for liquid transfer in unsaturated media [*Childs* and *Collis-George*, 1950] may be written

$$q_{liq}/\rho_w = -K\nabla\Phi \tag{9}$$

where q_{liq} is the vector liquid-flux density, gm cm⁻² sec⁻¹

K is the (unsaturated) hydraulic conductivity, cm sec⁻¹

Φ is the total potential, cm

If we regard Φ as comprising pressure and gravitational components

$$\Phi = \Psi + z \tag{10}$$

where z is the vertical ordinate, positive upwards.

It will be clear from the previous discussion that in the θ range where liquid transfer occurs ($K > 0$) Ψ is determined by capillarity, hence

$$\frac{\partial\Psi}{\partial T} = \frac{\Psi}{\sigma}\frac{d\sigma}{dT} = \gamma\Psi \tag{11}$$

Using (10) and (11) in (9), we obtain

$$q_{liq}/\rho_w = -K\gamma\Psi\nabla T - K(\partial\Psi/\partial\theta)\nabla\theta - Ki \tag{12}$$

where i is the unit vector in the positive z direction. Clearly (12) is of the form

$$q_{liq}/\rho_w = -D_{Tliq}\nabla T - D_{\theta liq}\nabla\theta - Ki \tag{13}$$

We have thus separated the liquid flux into three components, that due to the temperature gradient, that due to the moisture gradient and that due to gravity. The latter two have received rather detailed treatment elsewhere [*Klute*, 1952; *Philip*, 1955, 1957a]; our special interest here is with the thermal liquid diffusivity, $D_{Tliq} = K\gamma\Psi$. γ is temperature dependent, but we may reasonably adopt the constant value -2.09×10^{-2}°C⁻¹ as representative of the temperature range 10°C to 30°C. Using this value, and the K and Ψ data of Moore for Yolo light clay, we then obtain the

relationship for $D_{T\text{liq}}$ as a function of θ which is shown in Figure 1.

Here we tentatively accept the validity of this theory of the liquid transfer under temperature gradients. The results of *Richards* and others [1938] and *Gardner* [1955] suggest that the temperature coefficient of Ψ may exceed the temperature coefficient of σ. However the experiments of both papers include extraneous factors which make this interpretation of their data uncertain.

Interaction of Vapor and Liquid Phases

The disposition of liquid water in fairly dry media.—Let us examine the disposition of water in a fairly dry medium, so dry, we shall suppose, that liquid continuity does not exist or is, at any rate, so poor that K (and hence $D_{T\text{liq}}$) assume very small values; that is, $\theta < \theta_K$ where θ_K is the moisture content at which K falls to some small arbitrary fraction of its saturated value. (We use the term 'liquid' here to denote water capable of viscous flow. Of course, even when liquid continuity does not exist, the water molecules adsorbed on the surface of the matrix of the medium form bridges between the isolated pores or wedges of liquid water. According to *Quirk* [1955], a complete monolayer is adsorbed on soil at $h \simeq 0.20$; that is, at $\Psi \simeq -2.2 \times 10^6$ cm at 20°C.) The system will still contain liquid water, but this will occur (either wholly or almost wholly) in isolated pockets, filling small pores or forming wedges about the points of contact between the grains of the medium. Such an 'island' (as we shall call these pockets) is shown in Figure 2.

Movement of water through liquid islands during vapor transfer—The solid curves of Figure 2 show the two menisci of the island when it is in thermodynamic equilibrium with its surroundings. Note that the curvatures are equal. We now suppose that a vapor pressure gradient due to a temperature field produces a vapor flux in the direction indicated by the arrow of the figure. The resulting condensation at A and evaporation at B tends to decrease the curvature of A and increase the curvature at B. This continues until the capillary flow through the island produced by the growing difference of curvatures A and B equals the rate of condensation at A and the rate of evaporation at B. The broken curves represent the new menisci at A and B. It is easily checked that for all likely orders of magnitude of the island dimensions, the necessary change in curvature will be so small that it is simply and rapidly attained.

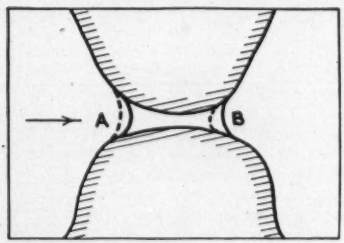

Fig. 2 – Moisture transfer through a liquid island. Arrow indicates direction of transfer

Moisture transfer in fairly dry media—We therefore regard moisture transfer under temperature gradients in fairly dry media as a series-parallel process of flow through regions of vapor and liquid. The vapor flux is determined by the vapor-pressure gradient across the air-filled pores; the flux through the liquid islands adjusts itself to equal this vapor flux.

A detailed analysis based on these ideas would involve investigation of the fine structure of the temperature and vapor fields in the air-filled pores. This would be very complicated and is not attempted here. Instead we evaluate q_{vap} on the basis of certain simplifying assumptions. We emphasize that this treatment must be regarded as no more than a first approximation; nevertheless it incorporates the essential ideas outlined above and will be seen to give results in fair agreement with the available experimental data.

The vapor flux density due to the temperature gradient in a single air-filled pore may be written as

$$-D_{\text{atm}} \rho_l h \beta (\nabla T)_a \qquad (14)$$

where $(\nabla T)_a$ denotes the temperature gradient in the pore. This expression follows immediately from equations (7) and (8) by substituting one for αa; its use presupposes similarity of temperature and vapor fields in the pore. This expression holds also for the mean flux density in all air-filled pores if, hereafter, we reinterpret $(\nabla T)_a$ as the average temperature gradient in these pores.

According to the ideas developed above, the total cross section available for transfer is equal to that occupied by air and liquid. We now assume that the mean flux density in the connecting liquid islands is equal to that in the air-filled pores, a concept which receives support from the above-mentioned property of the islands of accommodating the vapor flux.

The total vapor flux density due to the temperature gradient is thus

$$-(a+\theta)D_{atm}\beta(\nabla T)_a = -D_{Tvap}\nabla T \quad (15)$$

where D_{Tvap} now denotes the value of the thermal vapor diffusivity predicted by the revised theory. We introduce no tortuosity factor here since this is already taken into account in the average $(\nabla T)_a$.

The ratio η of the vapor transfer given by the present theory to that given by the simple theory follows from (7), (8), and (15)

$$\eta = \frac{a+\theta}{\alpha a} \cdot \frac{(\nabla T)_a}{\nabla T} \quad (16)$$

The first factor making up η, $(a+\theta)/\alpha a$, is simply evaluated. We denote the second, $(\nabla T)_a/\nabla T$, (that is, the ratio of the average temperature gradient in the air-filled pores to the overall temperature gradient) by the symbol ζ and proceed to indicate how it may be evaluated.

De Vries [1952ab] gives a method of calculating the thermal conductivity of soils by treating the soil as a continuous medium (water or air) in which 'particles' of soil and air or water are randomly dispersed. On the basis of certain plausible assumptions about the shape of these particles, values of the ratios between the average temperature gradients in the particles and in the medium can be computed from their respective thermal conductivities. The value of ζ follows immediately from these ratios and the volume fractions of the different components

$$\zeta = \frac{(\nabla T)_a}{a(\nabla T)_a + \theta(\nabla T)_w + (1-a-\theta)(\nabla T)_s} \quad (17)$$

where $(\nabla T)_a$, $(\nabla T)_w$ and $(\nabla T)_s$ are the temperature gradients averaged over the volumes occupied respectively by air, water, and solid.

Values of ζ at 20°C calculated in this way are shown in Table 2. Two values have been adopted for the thermal conductivity of the soil particles, namely, 7×10^{-3} cal cm^{-1} sec^{-1} °C^{-1}, which holds for most soil minerals [*de Vries*, 1952ab; *Smith*, 1942] and 20×10^{-3} cal cm^{-1} sec^{-1} °C^{-1}, which holds for quartz. The values computed for quartz are shown in brackets in the table. Values of the thermal conductivities of air and water at 20°C, 0.0615×10^{-3} and 1.42×10^{-3} cal cm^{-1} sec^{-1} °C^{-1}, were used. The additional apparent conductivity of the air due to the vapor transfer λ_{vap} was taken into account by the means indicated in the next section. Use of this table should give ζ accurately enough for approximate application of the theory in the temperature range 10°C to 30°C. Since λ_{vap} increases rapidly with increasing temperature it cannot be used for a wider range of temperatures.

Note on adsorbed phase—To this point we have neglected the possibility of transfer in the adsorbed phase. Examination of this aspect is complicated by the fact that surface migration is governed by the gradient of h rather than that of ρ. Part of the vapor that evaporates from or condenses on these surfaces may recirculate in a single air-filled pore through the process of surface migration. However, it seems unlikely to us that the total transfer can be much affected by diffusion in the adsorbed phase.

Note on terminology—A question of terminology arises. What we should call 'vapor' and what 'liquid' flux in this complicated series-parallel system. For some purposes there is little need to distinguish between the phases, but the distinction becomes important, for example, when the transfer of soluble salts under thermal gradients is studied.

We shall use the term 'liquid transfer' to describe the transfer which occurs exclusively in the liquid phase; all transfer in excess of the liquid transfer we shall term 'vapor transfer.' Thus in the absence of liquid continuity all transfer is vapor transfer. It is in this sense which we use D_{Tvap} in equation (15).

Moisture transfer with liquid continuity—When $\theta > \theta_K$ the preceding model fails. At moderate moisture contents continuity of both liquid and vapor phases may exist, together with islands of both phases. As θ increases still further vapor continuity fails and the system comprises vapor islands in a liquid continuum.

With increasing moisture content and increasing degree of liquid continuity, the liquid phase transfer due to temperature-induced capillary potential gradients becomes dominant. The decrease in vapor-induced transfer through the liquid islands may be attributed not only to a reduction in the number of islands and in the opportunity for vapor transfer, but also to a growth of the size of the

TABLE 2 – *Values of ζ at 20°C for different porosities and moisture contents*[a]

θ	Values of ζ for $a+\theta =$		
	0.7	0.5	0.3
0.0	1.4 (1.4)	1.9 (2.0)	3.0 (3.2)
0.1	1.3 (1.4)	1.7 (1.9)	2.0 (2.7)
0.3	1.5 (1.6)	1.7 (2.0)	2.1 (2.9)
0.5	1.5 (1.6)	1.8 (2.2)	
0.7	1.6 (1.8)		

[a] Note that for $a = 0$, ζ means $\lim_{a \to 0} \zeta(a)$.

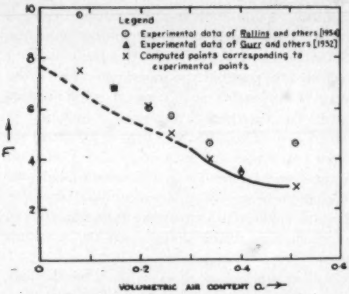
Legend
Experimental data of Rollins and others [1954]
Experimental data of Gurr and others [1952]
Computed points corresponding to experimental points
η
VOLUMETRIC AIR CONTENT a →

FIG. 3 – Ratio of 'vapor' transfer (either as predicted by present theory or observed) to prediction of simple theory, η, as a function of volumetric air content a; curve shows theoretical relationship for Yolo light clay.

islands which remain and an increase in the radii of curvature of the menisci to the point where automatic adjustment to the vapor flux is no longer possible.

This system will be even more complicated to analyze than the one without liquid continuity. It is reasonable to suppose, however, that, as θ increases above the value θ_K, the effective cross-section for combined liquid-vapor transfer will decrease steadily. This may be expressed by replacing $a + \theta$ in (15) by a factor $a + f(a)\theta$, where $f(a) = 1$ for $a \geq a_K$; a_K denotes the value of a at $\theta = \theta_K$. As a first approximation we tentatively propose $f = a/a_K$; thus $f \to 0$ as $a \to 0$.

In Figure 1 we show for comparative purposes $D_{T\text{vap}}$ for Yolo light clay computed by means of the present theory. In the calculations we assumed that the sand fraction of the soil (23.8 per cent) consisted of quartz; we also used the value $\theta_K = 0.2$, in accordance with Moore's data. The corresponding $\eta(a)$ relationships for Yolo light clay is shown by the curve of Figure 3. We recognize the uncertainty of the basis for computing η for $a < a_K$ by using a broken curve in this region.

We are now in a position to explain and reconcile the experimental data introduced at the beginning of this paper.

A RECONCILIATION OF THE FACTS

(a) *The large value of the apparent vapor transfer* —None of the methods employed by the experimenters listed in Table 1 distinguishes between pure vapor transfer and series-parallel transfer through a vapor continuum and liquid islands. (To the tabulated list we may add the technique of *Hadley* and *Eisenstadt* [1955], who attempted to distinguish the phases by using a radioactive tracer salt.) In other words, rather than distinguishing phases, these methods indicate as liquid phase movement only that which occurs exclusively in the liquid continuum; that is, the definitions of liquid transfer and vapor transfer we adopt agree with the suppositions of the experimenters.

The data of *Rollins* and others [1954] are the most suitable for a comparison of theory and experiment, since no appreciable liquid flow from cold to warm occurred in their columns, the cold and the warm side being connected by a capillary tube with a resistance to liquid flow small in comparison with the resistance of the column itself. As a consequence moisture was fairly evenly distributed in the columns throughout the experiments and in most experiments no moisture gradient existed in the center part of the column.

'Experimental' values of η deduced directly from their data are given in Table 1 and shown by open circles on Figure 3. The corresponding values of $\eta(a)$ predicted by the present theory (that is, computed from the data of *Rollins* and others [1954] on porosity, etc.) are shown by crosses. For computing points at small a, it was necessary to assume a value of $a_K(0.2)$, since no Ψ or K data were given for the silt loam of these experiments, and to adopt the values of f suggested in the previous section. The agreement between the experimental points and the theoretical values is quite satisfactory in view of the approximate character of the analysis and the possible experimental errors, which we estimate to be of the order of five to ten per cent. No explanation can be offered for the comparatively large discrepancy at $a = 0.51$; the experimental value for this case appears to be rather high in comparison with the other experimental data. For $a = 0.078$ the differences between observed and calculated values may be caused by the fact that the contribution of liquid flow ($= -D_{T\text{liq}}\nabla T$) has not been taken into account. This cannot be checked, however, as no data on $D_{T\text{liq}}$ are available for this soil.

The single experimental value of η given by *Gurr* and others [1952] is also in good agreement with the value computed from our theory. These are shown by the triangle and the corresponding cross on Figure 3. This may be partly fortuitous since the experimental value is an average over five days with changing moisture distribution. However, the vapor transfer was calculated by *Gurr* and others [1952] for "the plane at which the initial water content remained unchanged."

The large values of η deduced from the experi-

ments of Taylor and Cavazza have not been included in Figure 3 since the analysis of these experiments is greatly complicated by the presence of air gaps in the soil columns. From an estimate of the thermal conductivities of the soil slices we calculate the temperature gradient in these gaps to be about four times as large as the mean temperature gradient. This leads to a calculated vapor flux across the gaps adjoining the central slice approximately ten per cent higher than the observed flux. This could mean that the central slices act as 'islands' with moderately low resistance to moisture flow. In fact the observed moisture gradients in the slices would cause a flow from warm to cold. We stress, however, that these experiments cannot really be analysed quantitatively on the basis of the available data.

We revert to the experiments of *Rollins* and others [1954] to remark on the influence of temperature on the observed vapor transfer. These authors measured vapor transfer in the same columns (that is, at the same values of a and θ) over different temperature ranges; namely 40°C − 2°C, 30°C − 2°C, 20°C − 1°C, and 10° − 0°C. The temperature coefficient of the observed vapor transfer was only slightly smaller than that given by the simple theory, but agreed even better with that predicted by the present theory, this being due to a small negative temperature coefficient of ζ.

(b) *Effect of moisture content on net moisture transfer*—Before explaining the data of *Smith* [1943], *Jones* and *Kohnke* [1952], *Gurr* and others [1952] on the variation of thermal moisture transfer with mean initial moisture content, we recall that these experiments were on closed systems, so that their observations were not of total moisture transfer, but of the net transfer. When the mean moisture content was so low that no liquid continuity existed in the column (and this was so for the drier columns of these experiments), the net transfer observed was in fact equal to the total transfer. At this moisture level transfer will be exclusively vapor transfer (using the terminology we propose), so that the transfer increases rapidly with moisture content rather like $D_{T\text{vap}}$. Since in each column there will exist a range of θ, which increases with the net transfer, the experimental results will tend to represent a smoothed $D_{T\text{vap}}$ curve.

This situation changes radically once θ exceeds θ_K. Then a liquid phase return flow produced by the moisture gradient will tend to balance the thermal vapor transfer and reduce the net transfer. This will begin to operate when part of the column attains a moisture content greater than θ_K, and we should expect net transfer to decrease rapidly as θ increases, until it becomes effectively zero when the mean θ is a little in excess of θ_K. It follows that the maximum net transfer will occur at a mean θ somewhat less than θ_K; exactly how much less than θ_K will depend, among other things, on the length of the column and the duration of the experiment.

We recall the data of Jones and Kohnke and other investigators on the effect of texture on the point of maximum observed net transfer; namely, that this point occurs at small tensions but rather low moisture contents in coarse-textured soils, while in fine-textured soils it occurs at greater tensions but at relatively high moisture contents. The effect of texture on θ_K is entirely parallel to this [*Moore*, 1939]. This parallelism may seem fortuitous; however, the preceding discussion of the relationship between θ_K and the point of maximum transfer suggests the existence of a real physical relationship.

It is thus seen that the present theory accounts both for the rapid increase with mean moisture content up to the point of maximum net transfer and for the steep decrease as θ increases further. It also explains the way in which the effect of mean moisture content on net transfer varies with soil texture.

(c) *The transfer of latent heat by distillation*—According to the simple theory the heat flux by distillation would be $-LD_{\text{atm}}\rho a a h \beta \nabla T$ where L is the latent heat of vaporization of water. A similar expression was given by *de Vries* [1950a] in a first attempt to assess the influence of vapor diffusion on heat transfer in soils.

In subsequent papers *de Vries* [1952ab] developed a method of calculating the thermal conductivity of soils from their composition. Here a more rational method of taking the distillation effect into account, first suggested by *Krischer* and *Rohnalter* [1940], was adopted. In this method the contribution of vapor distillation to the heat transfer is first calculated for the air-filled pores separately. It follows immediately from (14) that this produces an apparent increase of the thermal conductivity in these pores by an amount λ_{vap} given by

$$\lambda_{\text{vap}} = LD_{\text{atm}}\rho h \beta \qquad (18)$$

(De Vries used an expression for λ_{vap} equivalent to (18) but with $h = 1$ and applied the results at moisture contents above 'wilting percentage.' For smaller moisture contents he assumed linear decrease of λ_{vap} with θ. Eq. (18) is more general,

applying to the full range of h and θ. Note that λ_l, $\lambda_l^{(v)}$ in *de Vries* [1952ab] correspond to our λ_a, λ_{vap}.) Then in calculating λ, the overall thermal conductivity of the soil, the value $\lambda_a + \lambda_{vap}$ is inserted for the conductivity of the air-filled pores, λ_a being the normal thermal conductivity of air.

This theory predicts thermal conductivities for a wide variety of soils and for the temperature range 0 to 75°C in good agreement with experimental data. (A difficulty arises in computing λ in a narrow range of low moisture contents for reasons unrelated to the present discussion. We refer to the original papers for treatment of this point.)

This second theory of the distillation effect is seen to be entirely consistent with the present theory of thermal moisture transfer. In principle one should also take into account sensible heat transfer by liquid flow through the islands. This can easily be shown to be negligible.

(d) *Effect of air pressure on apparent vapor transfer*—The explanation of the data of *Jennings* and others [1952] involved the concept of vapor diffusion as the governing mechanism and depended only on this aspect of the simple theory. The present theory retains this concept and therefore agrees just as well with the observation that transfer decreases as gas pressure increases.

The situation, then, is that the present theory retains the concept of vapor diffusion as the governing mechanism of transfer (at least in dry soils), which had received support from the observations of (c) and (d), and at the same time provides a quite comprehensive (and reasonably quantitative) explanation of the apparently conflicting evidence presented under (a) and (b).

Relation of the present theory to that of Smith [1943]—There are certain points of similarity between the present theory and that of *Smith* [1943]. The distinction is, essentially, that Smith envisaged the process of vapor distillation as triggering off the transfer in a series of discrete steps, while it appears to us that the process will very rapidly become continuous. By treating it as such we have been able to make this first attempt at analyzing the phenomenon quantitatively. In addition, we have, of course, attempted to take into account the fine structure of the temperature field in the medium.

The Equations of Moisture and Heat Transfer

We conclude this paper by presenting the system of equations which describe moisture and heat transfer under combined moisture and temperature gradients in porous materials. We begin by reverting to (7) for the vapor transfer, which we previously derived from the simple vapor theory; we now require to reinterpret the diffusivities of (7) in terms of the present theory.

The simple theory gives for the isothermal vapor diffusivity

$$D_{\theta vap} = \frac{D_{atm} \nu \alpha a g \rho}{\rho_w RT} \frac{\partial \Psi}{\partial \theta} \tag{19}$$

The mechanism of transfer operating in the thermal case fails here, since the vapor pressure gradient is now due solely to the moisture gradient, and, in general, very small changes in the curvature of a meniscus will be sufficient to reverse the direction of vapor movement. Accordingly, the simple theory may be expected to hold reasonably well for isothermal vapor transfer, that is, the values of $D_{\theta vap}$ given by *Philip* [1955] and (19) should be reasonably correct. (The D_{vap} of *Philip* [1955] corresponds to $D_{\theta vap}$ here. He omitted the factor ν (which, as we remark above, is close to unity for most applications to nature) and also the factor $1/\rho_w$, so that although numerically correct, his D_{vap}, as it stands, is in the units gm cm^{-1} sec^{-1}.) This view is supported by the data of *Staple* and *Lehane* [1954].

We also use here (12) and (13), describing liquid phase movement. Combining (13) with (7) we obtain

$$q/\rho_w = -D_T \nabla T - D_\theta \nabla \theta - Ki \tag{20}$$

where q gm cm^{-2} sec^{-1} is the total flux density of water, and

$$D_T = D_{Tliq} + D_{Tvap} \tag{21}$$

$$D_\theta = D_{\theta liq} + D_{\theta vap} \tag{22}$$

D_T, the thermal moisture diffusivity, has been computed for our illustrative Yolo clay and is shown in Figure 1. The relative constancy of D_T over a large part of the θ-range must be regarded as a coincidence due to the fact that in this case the maximum values of D_{Tliq} and D_{Tvap} are of about the same order of magnitude. We expect that in coarser-textured soils than the Yolo light clay the maximum value of D_{Tliq} will exceed the maximum of D_{Tvap} and tend to dominate the shape of D_T. Conversely, our expectation is that D_{Tvap} would be more important in finer-textured soils and would largely determine the shape of D_T. D_θ, the isothermal moisture diffusivity, has been discussed elsewhere [*Philip*, 1955].

Differentiating (20) and applying the continuity

requirement, we obtain the general differential equation describing moisture movement in porous materials under combined temperature and moisture gradients

$$\frac{\partial \theta}{\partial t} = \nabla \cdot (D_T \nabla T) + \nabla \cdot (D_\theta \nabla \theta) + \frac{\partial K}{\partial z} \quad (23)$$

Eq. (23) depends, among other things, on the uniqueness of the $\Psi(\theta)$ relation. The existence of hysteresis in $\Psi(\theta)$ [*Haines*, 1930], which may occur if some parts of the medium are gaining moisture and other parts are losing it, may invalidate the use of (20).

It is seen that the significant characteristics of the soil are the diffusivities, D_T and D_θ, and the hydraulic conductivity K. When more detail is required D_T and D_θ must be split into their components $D_{T\text{liq}}$, $D_{T\text{vap}}$; $D_{\theta\text{liq}}$, $D_{\theta\text{vap}}$. The two liquid diffusivities tend to be the most important ones at high moisture contents, whilst the two vapor diffusivities are dominant at low moisture contents.

Finally, we may write the heat conduction equation for the soil

$$C\frac{\partial T}{\partial t} = \nabla \cdot (\lambda \nabla T) + L\nabla \cdot (D_{\theta\text{vap}} \nabla \theta) \quad (24)$$

where C cal cm^{-3} °C^{-1} is the volumetric heat capacity of the soil and λ cal sec^{-1} cm^{-1} °C^{-1} is the thermal conductivity (including the thermal distillation effect). Eq (24) is more general than the customary equation, the second term on the right-hand side representing distillation effects induced by the moisture gradient. It will be noted that (23) and (24), both equations of the diffusion type involving θ- and T-dependent diffusivities and conductivities as well as gradients of both θ and T, together govern the simultaneous moisture and heat fields in the soil.

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A Correlation of the Characteristics of Great Storms

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Abstract—Four characteristics of a storm are the maximum precipitation at the center, or eye, the duration of the storm rainfall, the areal extent, and the shape. These are generally presented graphically by means of curves of relation between average precipitation and area, determined by volumetric integration outward from the center along isohyetal lines. This paper presents a method whereby storms may be compared by means of a mathematical correlation of the characteristics, which makes possible the combining of area-precipitation curves into a single relation. It was assumed that (1) the distribution of precipitation outward from the eye of the storm is an exponential relation with distance, (2) the isohyetals are geometrically similar, and (3) a characteristic area may be selected for each storm so that the depth-area curves may be reduced to dimensionless terms. These assumptions are combined mathematically into

$$\bar{P}/P_{10} = \frac{1.68}{A/A_{0.5}} [1 - e^{-1.68(A/A_{0.5})^{\frac{1}{2}}} (1.09(A/A_{0.5})^{\frac{1}{2}} + 1)]$$

in which $\bar{P}$ is the average precipitation, P_{10} is the maximum precipitation at the eye of the storm over ten square miles, A is the area enclosed by an isohyetal, and $A_{0.5}$ is the characteristic area, that within which the average precipitation is one-half the maximum. The validity of the equation was investigated by a study of a number of great storms that have occurred over the central Great Plains region. Curves of relation between depth, area, and maximum precipitation were prepared and a method suggested for the determination of maximum flood-producing storms for use in the design of flood-control works in the central United States.

Introduction—The rapidly increasing interest in the utilization of the surface waters of the United States is highlighting the need for more detailed knowledge of the nature and characteristics of the storms from which these surface waters are derived. Storage reservoirs can be designed properly only if the designer has at hand true patterns of storms which could strike a watershed. These design storms are now obtained by transposing the largest storm which has occurred nearby. Distance has made the transposition of some storms doubtful or the storms were of a shape or size such that when transposed over the watershed would not produce the maximum conditions of water volume or runoff rate. It is only by correlation studies of all the storms in a region that the most severe combination of characteristics for a given watershed can be established.

Storm characteristics—In this study, the fundamental characteristics of a storm are assumed to be (1) the maximum precipitation at its center, (2) its shape, as delineated by isohyetals, (3) its areal extent, and (4) its duration.

(1) Each storm has a center at which the precipitation is a maximum. Some storms have more than one such center. Because of a lack of rainfall reporting stations the actual maximum point precipitation for a storm is seldom measured, that over an area of ten square miles being taken as representative.

(2) The isohyetal representation of a storm may be likened to the topographic delineation of a hill. The average precipitation corresponds to the volume of the hill per unit area, measured along a selected contour or isohyetal. There is usually a geometric similarity among the individual isohyetals in portions of the storm, so that the area enclosed may be nearly directly proportional to the square of the distance outward from the storm center, measured along an axis.

(3) The areal extent of a storm, if defined as that area over which significant precipitation occurred, may vary from less than 100 sq mi for the intense local thunderstorms to more than 100,000 sq mi for the great storms such as those which invade the Ohio River valley. The area of significant precipitation is very difficult to determine. The zero isohyetal can be precisely drawn for few storms.

(4) The air masses which produce a storm may remain over a region for a few minutes, a few hours, or several days. The duration may thus vary widely. Generally, storms are analyzed for selected durations, up to the total time of the storm. Those selected for this study were 6, 12, 24, and 48 hours.

Mathematics of storm characteristics—The funda-

mental relation among the storm characteristics studied is that between the precipitation at a point within the storm and its distance from the storm center. A relation more suited to analysis is that between the precipitation within that part of the storm enclosed by an isohyetal and the area defined by the isohyetal and its distance from the storm center, measured along a selected axis. A study of thunderstorm rainfall made by the *U. S. Weather Bureau and the Corps of Engineers* [1947] indicates that for such storms the precipitation rate P along an isohyetal is an exponential function of distance from the storm center, thus, $\ln P \propto L$. This proportionality appears to hold for the much larger storms as well. It is expressed by

$$P = P_m e^{-aL} \tag{1}$$

in which P is the precipitation along any isohyetal, P_m is the maximum at the eye of the storm, a is a coefficient of distribution, and L is the distance from the storm center to the isohyetal, measured along an axis of the storm.

Since storms are analyzed on the basis of the areas enclosed by isohyetals, it is necessary to replace the distance L by an area equivalent. While the shape of a storm is usually highly irregular, the isohyetals which define the pattern approach similarity, geometrically, so that the relation between L and the corresponding area may be expressed by $L = kA^{0.5}$.
Substituting this in (1), it becomes

$$P = P_m e^{-akA^{0.5}} \tag{2}$$

Then, since storm data are usually given in terms of average precipitation versus area, it is necessary to integrate (2) with respect to area and to divide by the area to obtain the average precipitation $\overline{P}$. This equation is

$$\overline{P} = \frac{P_m 2}{a^2 k^2 A} [1 - e^{-akA^{\frac{1}{2}}} (akA^{\frac{1}{2}} + 1)] \tag{3}$$

Eq. (3) is the mathematical expression of the relation between average precipitation and areal extent for a storm having particular coefficients a and k. In this form the equation does not permit comparison of different storms. The coefficients can be eliminated by a modified form of dimensional analysis and the substitution of a characteristic area.

If the ratio of the average to the maximum precipitation $\overline{P}/P_m$ is set equal to 0.5 and (3) solved, it is found that $a^2k^2A = 1.18$. If the area which produces this precipitation ratio is designated as a characteristic area $A_{0.5}$, the relation becomes $ak = 1.09/A_{0.5}^{0.5}$. Substituting for the coefficient product in (3) and designating the maximum precipitation over ten square miles P_{10} as the maximum for the storm, the equation becomes

$$\frac{\overline{P}}{P_{10}} = \frac{1.68}{A/A_{0.5}} [1 - e^{-1.09(A/A_{0.5})^{\frac{1}{2}}} (1.09(A/A_{0.5})^{\frac{1}{2}} + 1)] \tag{4}$$

The assumption of an exponential relation between precipitation and storm area is by no means new. Over three decades ago *Horton* [1924] proposed the following relation between average precipitation, maximum precipitation at the center of the storm, and the storm area

$$\overline{P} = P_m e^{-kA^n}$$

From studies of data processed by the Miami Conservancy District, Horton found that five great northern storms of 24-hour duration produced an envelope curve for which $k = 0.0883$ $n = 0.24$, and $P_m = 16$; while for five great southern storms of the same duration $k = 0.112$, $n = 0.23$, and $P_m = 22$. For the northern storm curve average precipitations agree rather well with the studies presented in this paper, but for the southern storm curve Horton's results were about one-half those determined herein.

The solution of (4) is given in Table 1.

Analyses of storms—Data for checking the foregoing mathematical evaluation of the pattern of storms were taken from the compilation of storm rainfall in the United States prepared by the *Corps of Engineers* [1953]. This presents the average

TABLE 1 – *Computed relation between area ratios and precipitation ratios, solution of Eq. (4)*

Area ratio $A/A_{0.5}$	Precipitation ratio $\overline{P}/P_{10}$	Area ratio $A/A_{0.5}$	Precipitation ratio $\overline{P}/P_{10}$
0.00	1.000		
.01	.935	.60	0.580
.02	.895	.70	.555
.04	.855	.80	.535
.06	.825	.90	.515
.08	.805	1.00	.500
.10	.790		
		1.20	.470
.15	.755	1.40	.445
.20	.725	1.60	.420
.25	.700	1.80	.400
.30	.675	2.00	.380
.35	.655		
.40	.635	2.50	.340
.45	.620	3.00	.315
.50	.605	3.50	.285
		4.00	.260
		4.50	.240
		5.00	.225

TABLE 2 – *Maximum precipitation P_{10} and characteristic area $A_{0.5}$ for great storms over the central United States*

Storm[a]	Storm duration							
	6 hours		12 hours		24 hours		48 hours	
	P_{10}	$A_{0.5}$	P_{10}	$A_{0.5}$	P_{10}	$A_{0.5}$	P_{10}	$A_{0.5}$
	inch	sq mi	inch	sq mi	inch	sq mi	inch	sq mi
Gulf Coast								
LMV 2-5	7.6	9,200	9.9	34,000	12.6	43,700	13.9	68,300
LMV 2-18	7.5	4,200	10.2	17,000	12.4	32,000	15.2	42,000
LMV 2-20	15.0	5,400	15.4	8,200	20.0	18,400	27.4	15,000
LMV 4-24	8.5	3,700	15.8	3,200	22.1	6,700	34.8	7,700
SW 1-10	5.9	20,000	6.4	65,000	7.4	86,000	9.0	182,000
GM 3-4	6.9	12,000	12.6	9,200	24.1	8,400	30.8	15,600
GM 4-12	22.4	2,000	29.8	2,500	36.5	3,300	37.6	3,600
GM 5-20	20.5	660	20.5	700	...	...	...	...
GM 5-1	13.3	1,800	19.5	1,500	31.7	3,000	33.7	3,900
Southern Plains								
UMV 2-1	5.6	10,000	6.0	26,000	6.3	42,000	9.0	109,000
OR 5-6	3.4	20,000	4.4	44,000	6.6	57,000	9.3	102,000
SW 1-5	6.2	20,000	7.1	33,000	7.8	39,000	12.1	39,000
SW 1-11	9.4	4,200	10.0	7,200	11.4	9,000	14.5	28,000
SW 2-11	17.3	1,200	20.8	1,090	21.3	1,200	...	...
SW 2-18	18.4	640	23.4	1,500	23.6	1,600	23.6	1,800
SW 2-20	9.9	700	12.3	1,100	17.2	1,400	24.4	8,500
SW 2-21	15.9	700	16.7	910	16.7	1,080	16.7	8,000
Central Plains								
UMV 2-5	10.0	7,800	12.0	8,700	...	...	...	...
OR 1-15	3.4	42,000	6.0	37,000	7.3	75,000	9.5	104,000
OR 4-8	4.2	17,000	6.3	46,000	9.0	86,000	13.6	63,000
MR 1-10	6.9	6,800	11.5	7,700	14.7	6,500	15.4	9,200
MR 3-28A	20.6	280	22.2	340	22.2	340	22.2	340
MR 4-24	15.1	990	20.7	950	21.7	960	21.7	960
MR 7-2A	10.6	1,200	11.0	2,000	15.0	1,500	19.0	5,300
MR 10-2[b]	5.3	15,000	7.0	17,000	8.6	16,000	14.3	17,700
OR 5-11	3.6	20,000	4.5	40,000	5.0	117,000	5.3	262,000
SW 2-1	13.4	1,800	13.7	2,400	13.9	2,600	13.9	2,600
Northern Plains								
UMV 1-11	10.5	4,600	10.7	6,100	11.5	6,000	12.1	9,500
UMV 1-11A	10.5	4,550	10.7	5,600	11.5	5,400	11.8	6,800
UMV 1-22	8.5	2,100	11.5	4,000	12.4	5,400	14.4	15,000
GL 4-5	3.2	13,900	6.4	13,900	10.0	11,800	10.2	13,500
MR 4-21	10.5	4,400	11.7	5,500	13.3	7,500	14.2	11,000
MR 4-23	6.0	2,000	9.1	3,000	9.5	3,500	16.9	3,500

[a] Data taken from Corps of Engineers [1945], with supplemental data to December 31, 1953.
[b] Storm of the Kansas River flood, 1951.

depths over selected areas for several durations for several hundred storms.

Since the pattern and intensity of storm rainfall vary markedly from the Gulf Coast northward to the Canadian Border, the storms selected were grouped according to geographic provinces: Gulf Coast, Southern Plains, Central Plains, and Northern Plains. The storms selected occurred over the central plains of the United States, from the eastern face of the Rocky Mountains to the western slopes of the Alleghenies and from the Gulf of Mexico to the Canadian Border. Each of the storms studied is listed in Table 2, including the storm number, the maximum precipitation P_{10}, and the characteristic area $A_{0.5}$, for durations of 6, 12, 24, and 48 hours.

These storms were analysed in three ways: (1) The solution of (4) was compared with storm data. (2) The relation between maximum precipitation P_{10} and characteristic area $A_{0.5}$ was investigated. (3) Curves of maximum average precipitation with respect to storm area were developed and compared with data for maximum possible precipitation, prepared by the *U. S. Weather Bureau* [1947].

Relation between precipitation ratio and area ratio—Data for eight storms of widely varying characteristics were chosen from the compilation

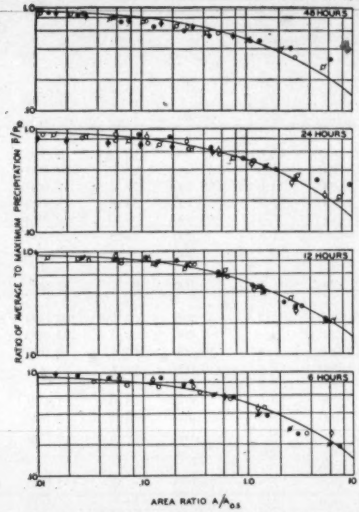

FIG. 1 – Relation between precipitation ratio and area ratio

of the Corps of Engineers for analysis to investigate the validity of (4). Their numbers are MR 1-10, MR 2-29, MR 6-15, MR 7-2A, MR 7-2B, OR 4-8, and SW 2-21. Precipitation ratios $\overline{P}/P_{10}$ and $A/A_{0.5}$ were computed and plotted, together with the solution of (4), for durations of 6, 12, 24, and 48 hours. These are shown in Figure 1. The agreement between the computed relation and those for the storms is good.

Relation between maximum precipitation and characteristic area—The data contained in Table 2 were plotted in Figure 2 for each of the durations, with the maximum precipitation P_{10} the ordinate, in rectangular coordinates, and the characteristic area $A_{0.5}$ the abscissa, in logarithmic coordinates.

Three lines have been drawn on each graph. The upper, marked G, is the envelope line for the greatest Gulf storms. That marked NP is the envelope for the Northern Plains storms. The third, marked $P_{\max}$, is the line representing the relation between maximum storm-center precipitation over ten square miles and the minimum characteristic area. In effect, it indicates the smallest, highest storm hills.

The most intense Gulf storm, that having the greatest precipitation P_{10} over the minimum characteristic area $A_{0.5}$, occurred in central Texas, with its center at Thrall (Taylor), on September 8–10, 1921, number GM 4-12. The most intense Central Plains storm occurred in eastern Colorado, at the head of the Republican River, on May 30–31, 1935, number MR 3-28A, and started a disastrous flood down that valley. While this latter storm is not in the area delineated as the Northern Plains, it is nearly so and was chosen as an envelope point on the Northern Plains storm line.

The triangle of storms—The three lines on Figure 2 are of considerable significance in these storm studies. Those marked G and NP delineate the envelope relations for the Gulf Coast and Northern Plains regions which, together with (4), may be used to establish curves of relation between areal extent and maximum average precipitation for these regions. Those marked $P_{\max}$ define the ten-square-mile precipitation of maximum intensity from the Gulf to the Northern Plains.

One of the characteristics of great storms appears to be that as the areal extent increases the precipitation at the storm center decreases, and as the storm becomes very large the regional spread of maximum precipitation decreases. In the central United States the effect of regional location of a storm becomes insignificant when the character-

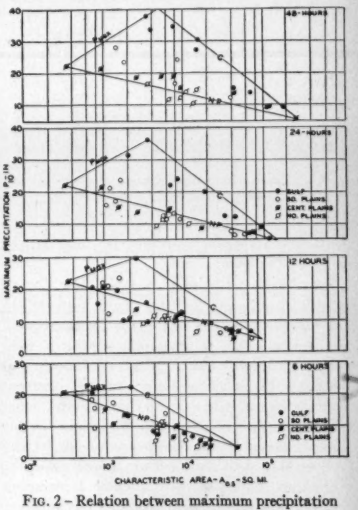

FIG. 2 – Relation between maximum precipitation and characteristic area

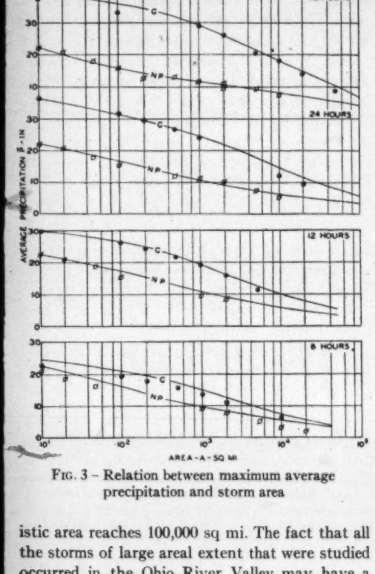

FIG. 3 – Relation between maximum average precipitation and storm area

istic area reaches 100,000 sq mi. The fact that all the storms of large areal extent that were studied occurred in the Ohio River Valley may have a bearing on this.

Relation between maximum average precipitation and area—If from the curves of Figure 2 a maximum precipitation P_{10} and corresponding characteristic area $A_{0.5}$ are selected and introduced into (4), its solution will produce a curve of relation between average precipitation $\overline{P}$ and areal extent A. For any storm area A there is one combination of maximum precipitation and characteristic area

TABLE 3 – *Characteristic area $A_{0.5}$ for selected areas of maximum average precipitation, in square miles, Gulf Coast and Northern Plains regions of the central United States*

Area of maximum average prec.	Characteristic area $A_{0.5}$							
	48-hour storm		24-hour storm		12-hour storm		6-hour storm	
	Gulf Coast	Northern Plains	Gulf Coast	Northern Plains	Gulf Coast	Northern Plains	Gulf Coast	Northern Plains
100	4,600	900	3,800	800	3,200	700	2,300	700
200	4,700	1,400	3,900	1,200	3,300	1,100	2,400	1,000
500	4,900	2,500	4,100	2,300	3,400	1,900	2,500	1,700
1,000	5,500	4,000	4,500	3,100	3,600	2,900	2,700	2,600
2,000	6,000	7,000	5,200	4,900	4,100	4,700	3,200	4,000
5,000	8,000	14,000	6,700	9,000	5,500	8,500	4,300	7,000
10,000	11,000	26,000	9,000	14,000	7,200	13,600	5,700	11,000
20,000	16,000	46,000	12,700	23,000	9,900	22,000	7,800	17,000
50,000	30,000	100,000	22,000	52,000	15,500	40,000	12,500	31,000

which will produce a figure of average precipitation that is a maximum for that area. By trial and error solution the maximum average precipitation for selected areas was computed and curves of relation developed (Fig. 3). Shown also on Figure 3 are the points of maximum average precipitation, taken from the storm data used in this study.

For each area over which the average precipitation is a maximum there is a corresponding characteristic area. Table 3 gives these characteristic areas for selected areas of maximum average precipitation.

The *U. S. Weather Bureau* [1946, 1947] has made studies to determine the maximum possible precipitation that may occur within the United States over areas from 10 to 500 sq mi and for durations up to 48 hours. These figures for the Gulf Coast and Northern Plains, together with those obtained from the correlation studies of this

TABLE 4 – *Precipitation, in inches, for selected durations and areas, as obtained by correlation studies and maximum possible precipitation, as reported by the U. S. Weather Bureau*

Determination	Area	6 hours		12 hours		24 hours		36 hours		48 hours	
		Gulf Coast	Northern Plains	Gulf Coast	Northern Plains	Gulf Coast	Northern Plains	Gulf Coast	Northern Plains	Gulf Coast	Northern Plains
	sq mi										
Correlation studies	10	25	23	30	23	36	22	38[a]	22[a]	40	22
Maximum possible	10	31	21	36	21	38	21	...	...	...	...
Correlation studies	200	20	14	25	15	29	18	32[a]	16[a]	35	14
Maximum possible	200	20	16	28	17	33	18	35	18	...	...
Correlation studies	500	17	11	22	12	27	12	30[a]	13[a]	32	13
Maximum possible	500	17	14	25	15	30	16	32	17	35	18

[a] Interpolated.

paper, are given in Table 4. One apparent inconsistency is noted. The correlation studies give slightly higher precipitations for ten square miles over the Northern Plains than the estimated maximum possible. Otherwise, the trend is proper. The spread is surprisingly small and the Texas and Colorado storms, which determine the apexes of the triangles of storms, closely approached the maximum possible precipitation which might have occurred from them.

Equivalent maximum storm—The design of a water-storage reservoir requires a study of that reservoir's operation under the effects of the maximum storm which may strike its watershed. Such a study usually includes transposition of the largest known storm which has occurred in a region close to the watershed and the maximum possible storm, produced by increasing precipitation depths in the maximum known storm on the basis of hydrometeorological studies. The transfer of a storm to a watershed requires the adjustment of its precipitation depths in accordance with direction and distance of transfer and air-mass analysis and the adjustment of the storm to the watershed by rotating the axis according to the orientation of the drainage. It is not always possible to find storms suitable for transfer within a reasonable distance of the watershed under study or to be sure they were the largest which might occur. The data presented in this paper make it possible to produce an equivalent maximum storm of geometric pattern, derived from those that have actually occurred, that will be suitable for at least preliminary reservoir design and operation studies and for checking storm transfers.

As an illustration of the manner in which an equivalent storm would be developed, let it be assumed that a watershed in southern Indiana is under investigation. This watershed is of such shape that a 500-sq-mi elliptical isohyetal with a ratio of major to minor axis of 2 to 1 would most effectively cover it. It is desired to develop the maximum equivalent 24-hour storm. (1) It is assumed that the area lies within a pluvial province that is 0.4 the distance from the Gulf to the Northern Plains. (2) From the curves of average precipitation versus area for the 24-hour storm, Figure 3, prorating the precipitation on the basis of the pluvial ratio, the average is found to be 20.5 inches. (3) The corresponding characteristic area $A_{0.5}$, obtained by prorating from Table 3, is 3,380 sq mi. (4) The area ratio $A/A_{0.5}$ is 0.148, which gives from Table 1 a precipitation ratio of 0.76. The average precipitation divided by this ratio gives a maximum precipitation P_{10} of 27.0 inches. (5) Since the shape of the storm isohyetals has been assumed to be an ellipse with a 2:1 ratio, solution of $L = kA^{0.5}$ gives $k = 0.798$.

Substituting for k and $A_{0.5}$ in the equation $ak = 1.09/A_{0.5}{}^{0.5}$ gives $a = 0.0235$. Substituting for P_m the ten-square-mile maximum P_{10} and the above value of a in (1), it becomes

$$P = 27.0e^{-0.0235L}$$

which is the equation of distribution of precipitation along the major axis of the equivalent maximum storm.

A test of the correctness of coefficient a and another means of obtaining it is to note that $aL = 1.09$ for the L distance of the characteristic area $A_{0.5}$. Incidentally, this means that the precipitation along the isohyetal which defines the area $A_{0.5}$ is closely $\frac{1}{2}$ the maximum P_{10}.

Acknowledgements—This paper was begun during basic planning studies conducted in the summers of 1952–55 by the author for the Iowa Natural Resources Council, Robert L. Smith, Director. It was carried to completion for the Indiana Flood Control and Water Resources Commission, J. I. Perrey, Chief Engineer.

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Heat Flow at Grass Valley, California*

SYDNEY P. CLARK, JR.

Abstract—Geothermal gradients, corrected for the effect of topographic irregularities, are calculated from the measurements of underground temperatures in the mines at Grass Valley, California. The gradient is 9.46 ± 0.16 °C/km for indefinitely persisting topography and 8.56 ± 0.16 °C/km if the topography has evolved in the last 10^8 years.

The mean thermal conductivity of 14 specimens of granodiorite from Grass Valley is 7.68 ± 0.09 × 10^{-3} cal/cm sec °C; that of 15 specimens of porphyrite is 7.14 ± 0.14 × 10^{-3} cal/cm sec °C.

Using the conductivity of the granodiorite, the heat flow is found to be 0.73 ± 0.01 × 10^{-6} cal/cm²sec and 0.66 ± 0.01 × 10^{-6} cal/cm²sec for the two physiographic histories assumed. No explanation of this low value can be deduced from this isolated determination.

A simplified form of correction for the effect of topographic irregularities on underground temperatures is presented.

Introduction—The low geothermal gradient at Grass Valley, California, enabled mining operations to be carried out at considerable depths without encountering high temperatures. The temperature is about 72°F at a depth of 3700 ft. Elsewhere, for example in the gold mines of the Rand or the oil fields of west Texas, low geothermal gradients are due to the high conductivity of the surrounding rocks, rather than to a low heat flow [*Bullard*, 1939; *Herrin* and *Clark*, 1956]. It is interesting to see whether this is also true at Grass Valley. The mines are located on the flanks of a high mountain range, and Bouguer anomalies in their vicinity reach about −60 mgal [*Duerksen*, 1949]. Hence there is reason to expect that the heat flow here should be higher rather than lower than 'normal' (0.9–1.3 × 10^{-6} cal/cm² sec). This expectation is based on the high rate of heat production in the acidic rocks that are usually thought to make up a mountain root [*Birch*, 1950].

Spicer [1941] gave a rough estimate of the heat flow at Grass Valley. His value was based on an estimated thermal conductivity of the rock, and he made no allowance for the effects of local topography on the geothermal gradient. Since the shafts of all the mines in which temperatures were measured are inclined, an appreciable error could conceivably be introduced by treating the surface of the ground as a plane. The geothermal gradient was therefore recalculated, and the thermal conductivities of 29 samples of rock from Grass Valley were measured.

Temperature measurements—Temperatures were measured in the Empire, North Star, Pennsylvania, and New York Hill mines by *Johnston* [1940, p. 21] who gives the following description of the measurements:

"These temperature observations were made in air or in standing water, usually on the drift face and always outside the path of air circulation. From three to six observations were made on each level, and the temperature given in the following table is an average for the level. The value for the North Star 9000 level is a rock temperature, obtained by averaging the readings of three maximum thermometers, which had remained for 24 hours in a bore hole four feet deep near an advancing face."

The drifts in all of the mines are roughly parallel to the topographic contours, and no serious error is introduced by the fact that the exact locations of the points of observation are not known. The temperatures were usually measured in air or water, and it is possible that a temperature lower than the true rock temperature was recorded. The results of such measurements are consistent with the rock temperature measured in the North Star 9000 level, however, and the self-consistency of the data suggests that the errors in the observations are not greater than a few tenths of a degree.

Most of the water entering the mines issued from well-defined shear zones, and over 90 pct of the water pumped from the Empire mine came from above the 4600 level, at a depth of about 1800 ft [*Johnston*, 1940]. Water moving in restricted portions of the rock will produce localized disturbances of temperature, and the self-consistency of the measurements supports the conclusion that circulating water has not appreciably affected the temperatures.

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Geothermal gradient—The temperature at a station near the surface of the Earth depends on the location of the station with respect to near-by topographic features and also on the rate and amount of uplift and erosion which produced those features. The theory of the topographic correction is given by *Birch* [1950], and his paper should be consulted for additional details. It is assumed that at a time t years ago the region was one of small relief, and that uplift commenced at that time. The uplift is assumed to be uniform and accompanied by erosion which proceeded linearly in time but at variable rates from place to place. Denote the total amount of uplift in time t by L, and the distance between the present (projected) elevation of the initial surface and the point on the present surface above the station by d. Then if T is the temperature at the station [*Birch*, 1950]

$$T - \alpha' Laz = \alpha z + (\alpha - \alpha')(daz - \bar{h}(t)) + T_0. \quad (1)$$

T_0 is the temperature of the surface at the point above the station, α' is the (negative) gradient of surface temperature with elevation, α is the geothermal gradient, z is the depth of the station, and $a = 2/\sqrt{\pi kt}$ where k is the thermal diffusivity. The topographic correction is contained in the term $\bar{h}(t)$; it is discussed in the next section.

The topographic correction—Birch [1950] distinguished two ways in which the topographic correction could be computed. In the 'three-dimensional' method, the topography around the station is divided into compartments by circles and radial lines, and the mean elevation in each compartment is estimated from topographic maps. The mean values are combined to give the total correction in a manner analogous to the computation of terrain corrections in gravity work. But if the topographic features near the station are sufficiently elongated, the relief may be thought of as dependent to a good approximation on only one Cartesian coordinate. In this 'two-dimensional' form, the correction can be obtained from a topographic profile, and the labor is greatly reduced.

Accuracy is lost in the two-dimensional form because the topography is never cylindrically symmetric in detail. Far from the station small departures from cylindrical symmetry are negligible, but they may be important near the station. This difficulty may be overcome by carrying the three-dimensional correction out to a certain distance from the station, and deriving the remainder of the correction from a two-dimensional approximation to the topography. This scheme of correction was devised for the reduction of temperatures in some of the great Alpine railroad tunnels [*Clark* and *Niblett*, 1956], but it has not been described previously. A derivation of the special function required in this form of correction is given in the appendix.

Calculation of the geothermal gradient—Three-dimensional topographic corrections were made above the North Star 9000 level and above the midpoints of the drifts of the Empire 2700 and 4600 levels and the Pennsylvania 1700 level. The positions of the levels were taken from diagrams given by *Johnston* [1940]. The three-dimensional correction was carried to a radius of 15,500 ft. The two-dimensional correction was made for one point at the center of the region.

In the calculation of the topographic correction, $\alpha - \alpha'$ was assumed to be equal to $\alpha/2$. *Spicer* [1941] found the geothermal gradient at Grass Valley to be 9.2°C/km, and α' was taken to be 4.6°C/km. The latter value is the average of the value 4.5°C/km estimated by *Birch* [1950] in the Front Range in Colorado and the value 4.7°C/km found in the Alps [*Clark* and *Niblett*, 1956]. No great precision in $\alpha - \alpha'$ is necessary, since the topographic correction is small.

The mean elevation of the surface of the ground above each mine level was estimated to the nearest 25 ft, and the topographic correction was interpolated from the points at which it was calculated. The greatest correction was about 40 ft. The uncertainties in the corrected depths are estimated to be about 50 ft.

The observed temperatures in the mines and, with one exception, the elevations of the mine levels were taken from *Spicer* [1941]. Several typographical errors in *Johnston's* [1940] paper were corrected in the later reference. There is a discrepancy in the elevation of the New York Hill 600 level, however. *Spicer* [1941] gives it as 1899 ft, but *Johnston* [1940, Fig. 30] shows the elevation as 2008 ft. The latter figure has been adopted in this work; if Spicer's elevation is correct, the geothermal gradients are increased by about two per cent.

Limiting values of the geothermal gradient may be calculated by assuming two models of the physiographic history of the region. The assumption of indefinitely persisting topography gives an upper limit to the geothermal gradient. The last important uplift in the Sierras took place in early Pleistocene times (10^6 years ago) according to

TABLE 1 – *Corrected temperatures and corrected depths*

Level	Corrected Temperature $T - a' Las$		Corrected Depth $z - \frac{1}{2}k(t) + \frac{1}{2}daz$	
	$t = \infty$	$t = 10^6$ years	$t = \infty$	$t = 10^6$ years
	°C	°C	m	m
Empire 1100	12.4	12.3	105	110
Empire 2700	14.7	14.5	320	330
Empire 3000	15.3	15.1	365	380
Empire 3400	15.5	15.3	410	420
Empire 3800	16.6	16.3	470	485
Empire 4200	17.2	16.9	530	550
Empire 4600	17.4	17.1	590	615
Empire 5000	17.9	17.5	655	680
Empire 5400	19.0	18.6	735	760
Empire 5800	19.5	19.0	815	845
Empire 6200	20.2	19.7	895	925
Empire 7000	21.6	21.0	1050	1090
Pennsylvania 1000	12.9	12.8	120	125
Pennsylvania 1400	13.5	13.4	205	215
Pennsylvania 1700	14.3	14.2	270	280
Pennsylvania 2100	15.1	14.9	335	345
Pennsylvania 2400	15.5	15.3	370	385
North Star 1900	13.6	13.5	175	185
North Star 8700	22.0	21.4	1070	1105
North Star 9000	22.4	21.8	1115	1160
New York Hill 600	13.1	13.1	75	80

Matthes [1930]. The maximum uplift since the Eocene is 2000 ft according to *Hudson* [1955]. Since tilting accompanied uplift, the mean uplift of the region as a whole was presumably less than this. To obtain a lower limit to the geothermal gradient, we assume that the region as a whole was uplifted 2000 ft, or 0.7 km, in 10^6 years. The distance d of (1) is taken to be 0.5 km. The thermal diffusivity k is found from measurements described in the next section to be 43 $km^2/10^6$ years.

The geothermal gradient is 9.46 ± 0.16°C/km for $t = \infty$, and 8.56 ± 0.16°C/km for $t = 10^6$ years. The standard deviation is 0.24°C in both cases. Corrected temperatures and corrected depths are given in Table 1 and are plotted in Figure 1 for $t = \infty$. Both Spicer and Johnston called attention to the fact that the temperature-depth curves calculated without the topographic correction are concave towards the depth axis. The topographic correction has removed any significant curvature. The temperatures that depart most widely from the regression lines were measured in porphyrite and diabase rather than granodiorite. The thermal conductivity of the former rock is less uniform than the latter, and this may account for part of the scatter of these points. Most of the scatter is attributable to small errors in the measurements of temperature and in the estimates of depth.

Thermal conductivity—The thermal conductivities of 29 samples of rock from Grass Valley were measured by the method described by *Birch* [1950]. The mines at Grass Valley are largely in a stock of granodiorite which is surrounded by porphyrite and diabase [*Johnston*, 1940], and the conductivities of 14 specimens of granodiorite and 15 specimens of porphyrite were measured. The conductivities of three samples of porphyrite were measured in three mutually perpendicular directions; in two of these samples, pronounced differences in conductivity were found, but it is not clear whether this is due to anisotropy or to inhomogeneity of the rock.

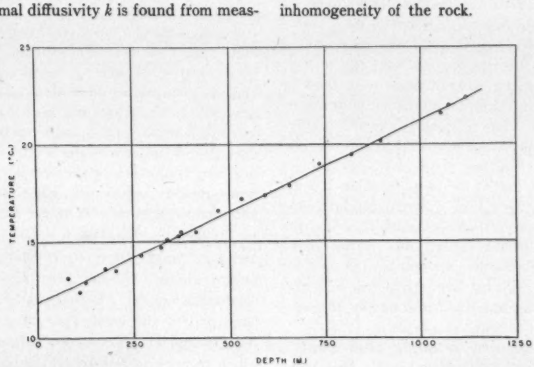

FIG. 1 – Temperature-depth curve for the steady-state assumption; solid circles represent temperatures measured in porphyrite and diabase; the remaining temperatures were measured in granodiorite

TABLE 2 – *Thermal conductivity and density*

Specimen	Conductivity	Density	Specimen	Conductivity	Density
	cal/cm sec°C	gm /cm³		cal/cm sec°C	gm/cm³
			Granodiorite[a]		
20	7.6×10^{-3}	2.73	27	7.5×10^{-3}	2.78
21	7.6	2.76	28	7.4	2.71
22	8.0	2.69	29	7.8	2.71
23	7.8	2.71	30	7.3	2.75
24	7.3	2.78	31	7.7	2.71
25	7.7	2.74	32	7.6	2.74
26	8.3	2.70	33	7.0	2.73
			Porphyrite[b]		
1	7.6×10^{-3}	2.74	8	6.5×10^{-3}	2.92
	7.5	2.77			
	7.4	2.77	9	6.5	2.74
2	8.0	2.75	10	7.9	2.73
	8.1	2.72			
	7.2	2.77	12	6.1	2.85
3	7.1	2.79	13	7.1	2.72
	7.8	2.75			
	7.6	2.75	14	6.8	2.87
4	6.8	2.86	15	6.5	2.75
5	7.2	2.76	16	7.5	2.73
7	6.2	2.84	18	6.6	2.74

[a] Mean conductivity = 7.61 ± 0.09; mean density = 2.731 ± 0.008.

[b] All measurements: Mean conductivity = 7.14 ± 0.14; mean density = 2.777 ± 0.013; All specimens: Mean conductivity = 6.96 ± 0.16; mean density = 2.785 ± 0.017.

The results of the measurements are given in Table 2. The samples of granodiorite are approximately normally distributed, but the distribution of the porphyrite appears to be bimodal. Because of the small number of samples, the bimodal appearance of the second distribution may not be real; alternatively, it may be the expression of anisotropy in this type of rock. Since all but three of the temperature measurements were made in granodiorite, no further examination of the question was made. The conductivity of the porphyrite was measured in order to investigate the possibility of the heat flow in the granodiorite being different from that in the porphyrite. Such a difference could arise from different conductivities in the two types of rock. Although the difference between the mean conductivities of the granodiorite and porphyrite is significant at the one per cent level, it is not large. Hence the heat flow in the granodiorite will be substantially the same as that in the surrounding porphyrite.

The mean conductivity of the granodiorite is $7.61 \pm 0.09 \times 10^{-3}$ cal/cm sec°C. This value should be increased by about one per cent because of the difference between the temperature of the specimens during the measurements (about 27°C) and the mean temperature in the mines (about 16°C) [*Birch* and *Clark*, 1940]. The corrected conductivity, $7.68 \pm 0.09 \times 10^{-3}$ cal/cm sec°C, will be used to calculate the heat flow. This value is larger than the value 0.006 cal/cm sec°C estimated by *Spicer* [1941], but it falls within the uncertainty which he assigned to his estimate.

Flow of heat—The heat flow at Grass Valley is $0.73 \pm 0.01 \times 10^{-6}$ cal/cm² sec for the steady-state assumption and $0.66 \pm 0.01 \times 10^{-6}$ cal/cm² sec for topographic evolution in 10^6 years. The best single value is $0.69 \pm 0.04 \times 10^{-6}$ cal/cm² sec. *Spicer* [1941] concluded that the heat flow was about 0.6×10^{-6} cal/cm² sec.

The heat flow at Grass Valley is significantly lower than the mean values found in other continental and oceanic regions [*Birch*, 1954]. It may be contrasted with the heat flow of 1.29×10^{-6} cal/cm² sec found by *Benfield* [1947] in Kern County, California. It is the lowest value recorded in the United States, although the heat flow in some of the mines in Ontario is nearly as low [*Misener*, *Thompson*, and *Uffen*, 1951].

The low heat flow at Grass Valley implies low temperatures in the underlying crust. Let us assume that the mean conductivity of the crust is 0.005 cal/cm sec°C. If all of the heat emerging from the Earth at Grass Valley originates below the crust, the temperature at a depth of 35 km is about 500°C. If half of the heat flow is due to crustal radioactivity (assumed independent of depth in the crust), the temperature at 35 km is only about 350°C.

The hypothesis of mountain roots suggests that high values of heat flow should be associated with negative Bouguer anomalies [*Birch*, 1950], and it is surprising to find an abnormally low heat flow on the flanks of a high mountain range. The geothermal evidence might be taken to imply that there is no root to the Sierras, but the large negative Bouguer anomalies found in the mountains require explanation. The nearest determination of heat flow is about 250 miles away, and conclusions based on a single isolated measurement would clearly be premature. It is not known whether the low heat flow represents a localized anomaly or is characteristic of a rather large part of the crust. The situation illustrates the inadequacy of the observational basis on which theories of the spatial distribution of heat flow rest. The relation between heat flow and major geological features is poorly known; a rela-

tion should exist, but its nature remains one of the outstanding problems of geophysics.

Acknowledgments—I am deeply indebted to Edmond F. Lawrence of the Nevada Bureau of mines for supplying samples from Grass Valley. This study would have been impossible without his generous assistance. The exacting task of shaping the rock samples for measurement was skillfully carried out by Donald C. Murphy and Harold J. Ames. I am grateful to Francis Birch for critically reading the manuscript and suggesting many improvements.

Appendix

In the modified form of the topographic correction, a special function analogous to the functions E and G of *Birch* [1950] is required. It will now be derived.

The temperature in the interior of a half space of uniform properties bounded by a plane surface on which the temperature is $f(x', y', t')$ is

$$T(x, y, z, t) = \frac{4kz}{\pi^{3/2}} \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{0}^{t} \frac{f(x', y', t')}{[4k(t-t')]^{5/2}} e^{-R^2/4k(t-t')}\, dx'\, dy'\, dt' \quad (2)$$

where $R^2 = (x - x')^2 + (y - y')^2 + z^2$ [*Carslaw* and *Jaeger*, 1947, pp. 229, 308]. If $f(x', y', t') = t'F(x', y')$, the integration with respect to t' can be carried out, giving [*Birch*, 1950, p. 586]

$$T = \frac{zt}{2\pi} \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} F(x', y') \frac{E(\beta)}{R^3}\, dx'\, dy' \quad (3)$$

Here $\beta = R/\sqrt{4kt}$

$$E(\beta) = 2\,\mathrm{erfc}\,\beta - 4i^2\,\mathrm{erfc}\,\beta$$

$$\mathrm{erfc}\,\beta = \frac{2}{\sqrt{\pi}} \int_{\beta}^{\infty} e^{-x^2}\, dx$$

$$i^2\,\mathrm{erfc}\,\beta = \int_{\beta}^{\infty}\int_{y}^{\infty} \mathrm{erfc}\, x\, dx\, dy$$

Consider a circle of radius r_0 drawn on the surface with its center at $x = y = 0$. If the temperature inside the circle is $t'F(x')$ and outside the circle is zero, then the temperature at the point $(0, 0, z)$ is

$$T = \frac{zt}{2\pi} \int_{-r_0}^{r_0} F(x')\, dx' \int_{\sqrt{r_0^2 - x'^2}}^{\sqrt{r_0^2 - x'^2}} \frac{E(\beta)\, dy'}{R^3}$$

$$= \frac{z}{4k\pi\beta_0^2} \int_{-r_0}^{r_0} F(x')\, dx' \int_{\beta_0}^{\beta_1} \frac{\beta_0^2 E(\beta)\, d\beta}{\beta^2\sqrt{\beta^2 - \beta_0^2}} \quad (4)$$

where $\beta_0 = \sqrt{\dfrac{x'^2 + z^2}{4kt}}$ and $\beta_1 = \sqrt{\dfrac{r_0^2 + z^2}{4kt}}$.

Denote the second integral by $H(\beta_0, \beta_1)$. Since $z\,dx'/(x'^2 + z^2) = d\psi$, where ψ is the angle in the plane $y = 0$ subtended at the station by a strip of width dx', (4) may be written

$$T = \frac{t}{\pi} \int_{-\psi_0}^{\psi_0} F(x') H(\beta_0, \beta_1)\, d\psi \quad (5)$$

where $\psi_0 = \tan^{-1}(r_0/z)$.

The function $H(\beta_0, \beta_1)$ was evaluated by nu-

TABLE 3 – $H(\beta_0,\beta_1)$

β_0/β_1	β_1										
	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
0.00	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.05	0.999	0.998	0.998	0.997	0.996	0.995	0.994	0.992	0.990	0.988	0.986
0.10	.995	.994	.992	.990	.987	.983	.978	.971	.964	.957	.949
0.15	.989	.987	.984	.979	.972	.963	.953	.942	.930	.917	.903
0.20	.980	.978	.973	.965	.953	.940	.924	.908	.891	.872	.851
0.25	.968	.966	.959	.947	.932	.914	.892	.871	.847	.821	.795
0.30	.954	.951	.941	.927	.908	.884	.858	.830	.800	.769	.736
0.35	.937	.933	.921	.903	.880	.853	.821	.787	.752	.714	.677
0.40	.917	.912	.898	.876	.849	.817	.781	.743	.702	.659	.618
0.45	.893	.887	.871	.846	.816	.781	.740	.697	.651	.604	.561
0.50	.866	.859	.841	.814	.781	.742	.696	.650	.601	.551	.504
0.55	.835	.828	.808	.778	.742	.700	.652	.602	.551	.499	.449
0.60	.800	.792	.770	.738	.699	.654	.605	.553	.501	.449	.397
0.65	.760	.752	.729	.695	.654	.608	.556	.503	.451	.399	.347
0.70	.714	.706	.683	.648	.605	.557	.506	.453	.401	.350	.300
0.75	.661	.653	.630	.595	.552	.504	.452	.401	.351	.303	.256
0.80	.600	.592	.570	.536	.493	.446	.396	.347	.300	.256	.215
0.85	.527	.519	.498	.467	.427	.384	.337	.292	.249	.209	.174
0.90	.436	.429	.411	.384	.350	.311	.271	.233	.196	.162	.132
0.95	.312	.307	.293	.273	.247	.219	.190	.162	.135	.109	.087
1.00	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000

merical quadrature, and its values are given as functions of β_1 and β_0/β_1 in Table 3. The results should be accurate to ± 0.001. For $t = \infty$

$$H(\beta_0, \beta_1) = \sqrt{1 - (\beta_0/\beta_1)^2} \qquad (6)$$

and this serves as a check on the calculation.

The temperature at $(0, 0, z)$ due to the temperature $t'F(x')$ over the entire plane surface is known to be [*Birch*, 1950]

$$T = \frac{t}{\pi} \int_{-\pi}^{\pi} F(x')G(\beta)\, d\psi \qquad (7)$$

where β now equals $\sqrt{\dfrac{(x - x')^2 + z^2}{4kt}}$,

$$G(\beta) = \beta^2 Ei(-\beta) + e^{-\beta^2}$$

and

$$-Ei(-\beta) = \int_{\beta}^{\infty} e^{-x}\, \frac{dx}{x}$$

The temperature due to a cylindrically symmetrical temperature distribution on the part of the surface lying outside of a circle of radius r_0 is then

$$T = \frac{t}{\pi} \int_{-\pi}^{\pi} F(x')G(\beta)\, d\psi - \frac{t}{\pi} \int_{-\psi_0}^{\psi_0} F(x')H(\beta_0, \beta_1)\, d\psi \qquad (8)$$

The integrals appearing in (8) may be reduced to finite sums by dividing the surface into strips parallel to the x-axis and taking mean values of the integrands in each strip. In order to calculate $F(x')$, imagine a reference plane passing through the point of the surface of the ground directly above the station. Let $\bar{h}_x$ be the mean difference in elevation between the surface of the ground in strip x and the reference plane. The term $\bar{h}_x$ is taken positive if the surface is below the reference plane. $F(x')$ may be related to the topography by

$$\bar{F}_x = (\alpha - \alpha')\bar{h}_x \qquad (9)$$

where $\bar{F}_x$ is the mean value of $F(x')$ in strip x and α and α' are the geothermal and surface-temperature gradients respectively. With the aid of this approximation, the topographic correction for the topography outside of a circle of radius r_0 may be computed. The complete correction is the sum of this correction and the correction for the topography within the circle, which is computed by the three-dimensional method. Thus we finally obtain

$$h(t) = \sum_r h_r E_r(R, t)\, \frac{\Delta\Omega_r}{2\pi} - \sum_{-r_0} \bar{h}_x \bar{H}_x(\beta_0, \beta_1)\, \frac{\Delta\psi_x}{\pi} + \sum_x \bar{h}_x \bar{G}_x(R, t)\, \frac{\Delta\psi_x}{\pi} \qquad (10)$$

$\bar{h}_j$ is the mean difference in elevation between the reference plane and the jth ring or strip. $\bar{E}_r(R, t)$, $\bar{G}_x(R, t)$, and $\bar{H}_x(\beta_0, \beta_1)$ are the mean values of the corresponding functions in the corresponding rings or strips, and $\Delta\Omega_r$ and $\Delta\psi_x$ are the solid or plane angles subtended at the station by a ring or strip. The first summation is carried over all of the rings into which the interior of the circle is divided, and the second two are over all of the two-dimensional strips.

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A Hypothesis of Formation of Mountains and Continents

B. D. Aggarwala and Edward Saibel

Abstract—It is shown that elastic instability in the Earth's crust due to cooling stresses is a plausible explanation of the formation of mountains and continents.

Introduction—There have been a number of attempts in recent years to explain the formation of continents and mountains. The two main currents of thought are that the mountains are formed either by slow convection currents lying beneath the surface of the Earth, or by some sort of elastic failure. While the view held by *Scheidegger* [1953] that "a combination of the two theories might in the end provide a satisfactory explanation for the observed patterns" is also held by the authors, it is interesting to examine how the formation of continents and mountains might have started in the beginning.

The model of the Earth assumed in this note is a liquid, spherically homogeneous (material properties function of radial distance only) Earth of visco-elastic material cooling radially from surface inwards. For mathematical simplification, the value of η, the co-efficient of viscosity in the calculations, is assumed to be zero above a certain critical temperature (the melting point of the material) and infinity below it, so that the cooling stresses are zero above this temperature and start developing after the material hardens.

We notice that temperature in this sphere increases with depth and therefore the critical temperature is reached at the surface first. As the sphere cools further it shrinks, and the surface crust, which has already hardened, tries to 'fit' the interior either by cracking at different points or by buckling. It is clear from this description that the internal pressure of the internal liquid mass on the surface crust is negligible at this stage. We may, therefore, for the purposes of determining the elastic deformation of this crust caused by cooling, consider it to be an elastic shell. The purpose of this note is to calculate the thermal stresses produced during cooling and to see which of the two above mentioned forms of elastic failure, cracking at different points or buckling, is more probable.

The problem of buckling of the crust has been treated by *Goldstein* [1926]. He takes a rectangular plate resting on an elastic foundation as the model of the crust and arrives at the result that the crust will be crushed before it buckles unless the thickness of the crust be less than 16 meters. We suggest that his model of a plate lying on an elastic foundation is unrealistic inasmuch as, after the crust buckles, the pressure on the crust from the liquid will not be proportional to transverse displacement as he assumes. The foundation on which the Earth's crust lies is a liquid surface (zero viscosity assumed), and the pressure exerted by this liquid foundation on the plate, in its buckled state, will be approximately uniform. If we assume that the foundation exercises a uniform pressure on the plate at any moment, then there is no effect on the critical buckling stress.

The problem of symmetrical buckling of a thin spherical shell has been discussed by *Timoshenko* [1940, pp. 491–497] and need not be reproduced here. His main result is that the critical stress at which the shell will buckle is given by

$$\sigma_{cr} = \frac{Eh}{a\sqrt{3(1-\nu^2)}} \tag{1}$$

where E is Young's modulus of the material, h is the thickness of the shell, a the outer radius, and ν is Poisson's ratio. The corresponding deformation is given by

$$w = B_n P_n(\cos\theta) \tag{2}$$

$P_n(\cos\theta)$ is the spherical harmonic of degree n, and B_n is a constant. The value of n is to be found by minimizing the expression

$$\varphi = \frac{(1-\nu^2) + \alpha[\lambda_n{}^2 + 2\lambda_n + (1+\nu)^2]}{\lambda_n + (1+3\nu)} \tag{3}$$

where $\lambda_n = n(n+1) - 2$, $\alpha = h^2/12a^2$, the quantity λ_n, as is apparent from this, is an integer. However if we consider it as a continuous variable and put $\partial\varphi/\partial n = 0$ then we get approximately

$$\lambda_n = -(1+3\nu) + \sqrt{\frac{1-\nu^2}{\alpha}} \tag{4}$$

In general, this value will give a non-integral value for n between, say, m and $m+1$. If we substitute the corresponding values of n in (3), the one that minimizes φ will correspond to the correct value of n.

In our case, if we put $\nu = 0.25$, $h = 20$ km, and $a = 6400$ km, this gives approximately $n = 32$. The corresponding half wave length is about 250 miles. This is quite reasonable. To find the maximum thickness of the shell at which the shell would buckle rather than fail, we substitute in (1) $E = 5 \times 10^{11}$ dynes/cm^2, $\nu = 0.25$, $\sigma_{cr} = 1.5 \times 10^9$ dynes/cm^2, $a = 6400$ km, giving approximately $h = 32$ km.

This means that for a shell of thickness of up to 32 km, the strength of the Earth is sufficient to transmit stresses by buckling rather than by releasing them locally by elastic fracture. This indicates that during the cooling of the Earth, if the cooling stresses would reach the critical stress by the time the Earth cools down to a depth of 32 km, the shell would buckle rather than fracture.

We proceed next to calculate the cooling stresses in a sphere. The stress-strain relations for a viscoelastic body may be written as

$$\frac{\partial \boldsymbol{\gamma}}{\partial t} = \left[\frac{1}{2\eta} + \frac{1+\nu}{E}\frac{\partial}{\partial t}\right]\mathbf{T} \tag{6a}$$

$$\frac{\partial \theta}{\partial t} = 3\,\frac{1-2\nu}{E}\frac{\partial \Theta}{\partial t} + 3\,\frac{\partial \epsilon}{\partial t} \tag{6b}$$

where $\boldsymbol{\gamma}$ is the deviatoric strain dyadic, θ is the cubical dilatation, Θ is the mean tension, T is the temperature, α is the coefficient of expansion, η is the viscosity of the material, and

$$\epsilon = \int^T \alpha dT$$

where t is time and $\mathbf{T}$ is the deviatoric stress dyadic having radial component $\mathbf{T}_r$.

The equation of equilibrium in the absence of body forces is

$$\frac{\partial \sigma_r}{\partial r} + \frac{2}{r}(\sigma_r - \sigma_\varphi) = 0 \tag{6c}$$

and the equation of compatibility is

$$\frac{\partial \epsilon_\varphi}{\partial r} - \frac{1}{r}(\epsilon_r - \epsilon_\varphi) = 0. \tag{6d}$$

Solving these equations simultaneously with boundary conditions $\sigma_r = \sigma_\varphi = 0$ at $t = 0$, $\sigma_r = 0$ at $r = a$ where a is the radius of the sphere, we get [*Rongved*, 1956, p. 16]

$$\mathbf{T}_r = 4\beta e^{-\psi(r,t)} \int_0^t e^{\psi(r,\lambda)} \frac{\partial}{\partial \lambda}\left[\frac{1}{r^3}\int_0^r \rho^3 \frac{\partial \epsilon}{\partial \rho}\, d\rho\right] d\lambda$$

$$\sigma_r = 3\int_r^a \frac{\mathbf{T}_r(\rho,t)}{\rho}\, d\rho, \qquad \sigma_\varphi = \sigma_r - \tfrac{3}{2}\mathbf{T}_r \tag{7}$$

where ρ is density,

$$\beta = \frac{E}{6(1-\nu^2)}, \qquad \psi(r,t) = \beta\int_0^t \frac{d\lambda}{\eta(r,\lambda)}$$

and σ_r and σ_φ denote radial and tangential stress components.

Integrating (5) by parts, we get

$$\mathbf{T}_r = 4\beta e^{-\psi(r,t)} \int_0^t e^{\psi(r,\lambda)} \frac{\partial}{\partial \lambda} \cdot \left[\epsilon(r,\lambda) - \frac{3}{r^3}\int_0^r \epsilon(\rho,\lambda)\rho^2\, d\rho\right] d\lambda \tag{8}$$

Eq. (7) and (8) give us cooling stresses in a sphere as a function of time and distance from the center.

Assuming, for the sake of simplicity, that at any point inside the Earth, viscosity is zero above the melting point and infinity below it, and assuming further that at $t = 0$, the Earth was at its melting point at all depths, (8) reduces to

$$\mathbf{T}_r = 4\beta\left[\epsilon(r,t) - \frac{3}{r^3}\int_0^r \epsilon(\rho,t)\rho^2\, d\rho\right] - 4\beta\left[\epsilon(r,t_0) - \frac{3}{r^3}\int_0^r \epsilon(\rho,t_0)\rho^2\, d\rho\right]$$

where t_0 is the time at which the temperature at the point reaches the melting point, that is, the time 'zero' in the present case. Thus, the expression reduces to

$$\mathbf{T}_r = 4\beta\left[\epsilon(r,t) - \frac{3}{r^3}\int_0^r \epsilon(\rho,t)\rho^2\, d\rho\right]$$

At any moment we may assume that cooling below a certain depth (say, for $r < r_1$) has been inappreciable, and for $r > r_1$, uniform, so that we get $\mathbf{T}_r = 4\beta\epsilon(t)(r_1^3/r^3)$, $r \geqslant r_1$; then

$$\sigma_\varphi = 4\beta\epsilon r_1^3\left[\frac{1}{r^3} - \frac{1}{a^3}\right] - 6\beta\epsilon\frac{r_1^3}{r^3}$$

The first term may be neglected in comparison with the second and we get approximately

$$\sigma_\varphi = -6\beta\epsilon = \frac{-E\epsilon}{1-\nu}$$

Finally, taking $\nu = 0.25$, $E = 5 \times 10^{11}$ dynes/cm^2, $\sigma_\varphi = \sigma_{cr} = 1.5 \times 10^9$ dynes/cm^2 and $\alpha = 7 \times 10^{-6}$/1°C, we get

$$\int dT = -321°\text{C}.$$

That is, the cooling stresses are so high that the failure stress would be reached in the shell almost

immediately. What the actual thickness of the crust will be at the moment when sufficient cooling has occurred to make the shell buckle, depends upon the rate at which the Earth cools. The latter in turn depends upon the distribution of radioactivity in the Earth. To calculate this thickness is not the purpose of the paper. We can safely assume, though, that if the crust has cooled down to a thickness of say 20 km (we use 20 km solely for illustrative purposes; we could as well consider other thicknesses), there would be sufficient cooling stresses developed in the shell to make it buckle and at this thickness, because the shell would buckle rather than fracture, we think that, to begin with, the former would be a more probable mode of deformation.

At this moment, though, the Earth would be so hot throughout that there would be no water except in the form of vapor and we might well suppose that the depressions in the shell (after it has buckled) would later on appear as oceans and the humps as continents and mountains.

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Progress Report, Seismological Laboratory California Institute of Technology, 1956*

H. Benioff, B. Gutenberg, F. Press, and C. F. Richter

Station Development

New stations—Palos Verdes: 33° 45.5′ N, 118° 21.4′ W, h = 340 meters, short- and long-period Benioff vertical. Installed March 21, 1956.

Hayfield: (Hayfield pumping station, Metropolitan Water District) 33° 42.4′ N, 115° 38.2′ W, h = 440 m; temporary equipment: short-period Benioff horizontal, which has recorded an unexpectedly large number of shocks at short distances. Installed June 20, 1956.

El Centro: 32° 47.8′ N, 115° 32.9′ W, h = −15 m. Strong-motion unit recording on film; N, E, Z with periods 0.8 sec, damping near critical, magnification 125 viewed on projector with 8× magnification. Installed November 28, 1956.

Additional instruments (*F. Press*)—Three components of the Press-Ewing moving-coil seismograph with To = 30 sec and Tg = 90 sec are being installed in Pasadena. The vertical and NS components are already in operation. The instruments are stable and require little attention. The version being used is one engineered by the Lehner and Griffith Co. of Altadena, California.

These seismographs have demonstrated their usefulness in many ways. Often they record long-period body waves and surface waves with a clarity which makes possible an interpretation otherwise difficult.

Instrument Development

Revised design of vertical reluctance seismometer (*H. Benioff*)—Revisions of the vertical component reluctance seismometer design was undertaken in order to eliminate the response to buoyancy variations of the atmosphere. The first attempt consisted in surrounding the instrument with a thick steel cylinder sealed to the base plate with a rubber O ring. Surprisingly, this change produced no effective reduction in the buoyancy response even though the cylinder walls and base plate were adequately thick to reduce pressure variations within the cylinder to a small fraction of their external values. The continuing response was finally traced to minute flexure of the base plate. Since the three pillars supporting the pendulum were attached to the outer portion of the base plate and the fixed portion of the transducer was attached to the central part of the plate, a flexure of the base plate produced a direct deflection of the pendulum relative to the fixed transducer element and thus resulted in a substantial response to buoyancy variations. In order to overcome this, a completely revised form for the entire instrument was effected. The pendulum is supported by a single central tubular column. The steady mass is in the form of a thick hollow cylinder surrounding the central pillar. The alloy supporting spring is located within the central supporting tube. Six rods forming a Willmore-type suspension serve to constrain the pendulum to move vertically only. A pressure-tight cylinder surrounds the instrument to reduce pressure variation on the inertia reactor. The outer dimensions of the pressure cylinder is thus reduced to 10.5-inch diameter and the instrument height is 28 inches. The response to atmospheric buoyancy variations is reduced to a satisfactory low level.

Modification of the reluctance seismograph for the recording of long period waves (*H. Benioff*)—Recordings with the long-period strain seismograph Tg = 180 sec revealed the existence of remarkable long period seismic waves in the period range one to 60 minutes or possibly even longer. Since a vertical component strain seismograph is not feasible, modifications have been made in a reluctance pendulum instrument to adapt it to the recording of the vertical component of these long-period waves. The new seismometer form mentioned in the preceding paragraph serves as the responding element. The pendulum period is increased to two seconds by increasing the transducer magnetic field. The transducer coils are wound with fine wire to increase their total series resistance to 125,000 ohms approximately. The galvanometer has a period of 180 sec and its field strength is increased sufficiently to make the critical damping resistance 125,000 ohms. A 100-mfd capacitor is shunted across the transducer seismometer coil in order to reduce the response to short-period waves in the range up to about 30 sec. The recording drum speed is reduced to 7.5 mm/min. Seismograms written with this instrument appear quite differ-

* Contribution No. 813, Division of the Geological Sciences, California Institute of Technology, Pasadena, California.

ent from the usual forms. The surface waves with periods ranging up to about 20 sec which dominate the ordinary seismogram are recorded with relatively small amplitudes, thus permitting longer period pulses, heretofore obscured, to be observed. A new galvanometer, with period of ten minutes, for use with this seismograph was designed by F. E. Lehner and is now being constructed.

Ink-writing seismograph (*H. Benioff*)—A new ink-writing seismograph has been set up to replace the older model in use at the Seismological Laboratory. The new instrument employs a reluctance vertical seismometer of standard design coupled to a tubeless galvanometer photocell-galvanometer amplifier of the type described in our previous report. Output from this amplifier drives the ink writing galvanometer which has a period of 0.3 sec. Control of the response characteristic is effected by means of capacitors shunted across the seismometer.

IGY Participation

Strain meter installation in South America (*H. Benioff*)—A set of two mutually perpendicular fused-quartz strain meters are being installed at Santiago, Chile, on an IGY project sponsored by the National Science Foundation. The meters will be provided with micrometer microscope measuring assemblies for measuring secular strains and ink writers for recording tidal strains and long period seismic waves. A similar installation is projected for location in Peru under the same auspices.

Antarctic seismograph station (*F. Press*)—Three components of the Press-Ewing seismograph are being installed in Antarctica at the Knox Coast station as part of the IGY effort. It is intended to use *Lg* waves and Rayleigh waves to study the crustal structure of Antarctica and to deduce the mean thickness of ice. The instruments will also provide data for epicenter location and for the determination of local seismicity.

Mantle-Crustal Rayleigh Waves (F. Press and H. Benioff)

It has been shown that Rayleigh waves may be represented by continuous dispersion curves in the period range 10–500 sec. Experimental data for oceanic paths were lacking, however, in the period range 40–100 sec. The difficulty in obtaining data in this range is due to the occurrence of a maximum in group velocity which results in two systems of waves arriving simultaneously. The new long-period vertical instruments described in the preceding paragraphs produce seismograms in which the short period crustal Rayleigh waves are reduced in amplitude relative to the simultaneously arriving mantle waves so that each may be analyzed separately.

The excellent response of the new instruments to waves with periods greater than 40 sec has made possible the frequent recording of mantle Rayleigh waves. Previously thought to be excited by certain great earthquakes, mantle Rayleigh waves are now being observed from some earthquakes with magnitudes as small as 6¼. This suggests fundamental differences in mechanism of origin involving the extent and time variation of the initial fault movement.

A striking feature is the almost impulsive initiation of the mantle-crustal waves, as would be expected for a maximum in group velocity. This feature, together with the superposed direct and reverse dispersion, presents a unique event on seismograms, one so easily recognizable as to facilitate the location of the epicenter.

Channel *P* Waves Π_g in the Earth's Crust (F. Press and B. Gutenberg)

The prominence on seismograms of channel S waves (*Lg*) suggests the existence of the corresponding longitudinal wave (Π_g). Examination of seismograms from North American stations for the Kern County earthquake of 1952 revealed the existence of this phase. It is characterized by small amplitude and erratic occurrence. The weakness of Π_g in contrast to the great strength of *Lg* is interpreted in terms of propagation in a crustal channel bounded on top by the Earth's surface.

Low-Velocity Layers (M. Båth)

Theoretical computations, using ray theory, have been made of the extent of the shadow zone, travel times, and energies of longitudinal waves for various focal depths, assuming an asthenosphere low-velocity layer.

Rigidity of Earth's Core (F. Press)

The rigidity of the core was measured from the amplitude ratio of twice reflected shear waves to once reflected shear waves under conditions of near vertical incidence. Huancayo seismograms of intermediate depth earthquakes were used in this study. A maximum value of core rigidity of 10^{11} dynes/cm^2 was found with indications that the actual rigidity is at least an order of magnitude smaller. The maximum value for the average dissipation constant for 11-sec shear waves in the mantle is $1/Q \sim 200 \times 10^{-5}$.

Damping of the Earth's Free Nutation (B. Gutenberg)

It is believed by several authors that the complicated motion of the Earth's poles indicates heavy damping. Schweydar showed in 1919 that it can be explained with good approximation as a beat phenomenon between the free period of the earth of about 14 months and a periodic displacement (range about three meters) of the Earth's axis of inertia due to movements of air masses from the northern to the southern hemisphere and back with a period of 12 months. On reasonable assumptions damping of this polar motion should be much lower than assumed by some authors and may be related to the time of relaxation of the order of 1000 years found from the study of the postglacial uplift and earthquake foci at great depths.

Seismic Activity 1897 to 1904 (B. Gutenberg)

Records of undamped Milne pendulums can be used to determine magnitude and energy of shallow earthquakes and have permitted extensions of the list of great earthquakes back to 1897 (see list of publications).

Energy of Earthquakes (B. Gutenberg)

Energy release in great earthquakes has been recalculated. The greatest shock between 1896 and 1955 was possibly the one off Colombia-Ecuador on January 31, 1906, $m = 8.1$ to 8.2, $E = 2 \times 10^{25} \pm$ ergs. During the period from 1896 (the year with the earliest useful data) to 1906 the average annual energy release in shallow shocks (about 2×10^{25} ergs per year) was about 3½ times the average release between 1907 to 1956; the greatest energy release in any calendar year was 5×10^{25} ergs in 1897, the smallest, in 1954, about 10^{24} ergs. The maximum annual release in intermediate and deep shocks during the years 1904 to 1955 was respectively 10^{25} ergs in 1914 and 3×10^{24} ergs in 1906.

Earthquake Energy, Earthquake Volume, Aftershock Area, and Strength of the Earth's Crust (C. Tsuboi)

The ultimate mechanical stress energy that can be stored in a given volume until a break-down takes place in its may be identified with the energy of the largest possible earthquake. The energy deduced on this hypothesis agrees well with those of the actual largest earthquakes. The area A in which aftershocks occur has been found by Utsu and Seki to increase with the magnitude M of the main shock. This relation, when combined with the magnitude-energy relation yields $E = 6 \times 10^{2} \times A^{1.5}$. The numerical values of the coefficient and of the exponent of A can be explained by the hypothesis stated above regarding the spatial distribution of the stress energy within the Earth's crust.

Travel Times at Short Distances (C. F. Richter and Assistants)

Data are being assembled on recorded times for shocks of magnitude near 3. These are large enough so that the timing of first arrival at the nearer stations are dependable, while the time of S can be read from the records of the less sensitive instruments. Only epicenters fairly well surrounded, or relatively close to a station, are used. The majority are in the Kern County area; here the results can be correlated closely for those of the aftershocks of 1952–1953 previously studied, most of which were of magnitude 4 and over and consequently could not be read for S at short distances. A good representation of shocks elsewhere in Southern California has also been examined. The total thus far worked out numbers about 60. The evidence establishes clear instances in which the origin time calculated from S–P at the nearest stations agrees well with that found from the other data, and also others in which it is definitely about one second earlier. The times of arrival of Pn at the more distant stations are also being included in the study, but results are less positive because of small amplitudes and possible late reading.

Crustal Structure at the Continental Margin (F. Press)

The phase velocity method of determining crustal thickness was applied to the San Francisco Bay region. Evernden's data on the phase velocity of Rayleigh waves was interpreted to indicate a thickness of 30 km. This may be compared with Tocher's results of 27–32 km based on refraction measurements, providing a good check on the method. The thinner crust here agrees with the results for the Southern California coast reported last year and may be taken as an indication that crustal structure in coastal California is influenced more by proximity to the continental margin than to the mountains.

In order to extend this method so as to obtain the structure of the offshore region, a seismograph station is being established on San Nicolas Island with support from the Office of Naval Research.

Effects of Ground on Shaking in Earthquakes (B. Gutenberg)

Five identical *EW* standard torsion seismographs are being operated temporarily at various locations in and near Pasadena. Their records are compared with the corresponding records written simultaneously at the Seismological Laboratory (on weathered granite). The thickness of the alluvium is one of the main elements affecting the amplitude and duration of shaking. In nearby as well as in distant shocks, waves with lengths of about three miles (corresponding to periods of roughly one second in longitudinal waves and of roughly one and a half to two seconds in transverse waves), show amplitudes on the campus of the California Institute and at the Huntington Library (both on alluvium nearly 1000 ft thick) which are frequently about five times the amplitudes recorded at the Seismological Laboratory. This ratio is smaller at locations with a thin layer of alluvium and about one for stations on bed rock. It has a well defined maximum for waves with periods of about 1 to 1½ sec on the campus of the California Institute and at the Huntington Library, but at stations with bed rock closer to the surface the maximum ratio is observed for waves with periods of one half second or less. Waves having periods of over five sec record with nearly the same amplitudes at all locations.

In nearby shocks relatively strong shaking continues on thick alluvium much longer than on the grounds of the Seismological Laboratory (Fig. 1). An instrument in the basement of the Washington Junior High School (located on a small peak of crystalline rock protruding above the alluvium) usually records amplitudes of the same size as those at the Laboratory. At the San Rafael School on deep tertiary sediments, less than a mile south of the Laboratory, the maximum amplitudes in nearby shocks (periods of less than ½ sec) are usually a few times those at the Laboratory, but relatively strong shaking does not last much longer than at the Laboratory.

Seismicity of the Earth (B. Gutenberg and C. F. Richter)

Seismicity continued generally low. There were less than 20 shocks of magnitude 7 or more, nearly all below 7½, probably none above 7.7.

Agua Blanca (Lower California) Shocks (C. F. Richter and Assistants)

On February 9, 1956, at 14h 32m 38s GCT (06h 32m 38s PST) an earthquake of magnitude near 6¼ originated near 31° 45′ N, 115° 55′ W, in the vicinity of El Alamo and San Miguel, Lower California. A fault trace was formed with right-hand strike-slip as well as dip-slip. Aftershocks were extremely numerous, and many were of magnitude 5 or more. One 52 min after the principal shock, and two on February 14–15, exceeded magnitude 6. The two latter had epicenters near 31° 30′ N 115° 30′ W; it is probable that faulting in the first earthquake extended eastward to this vicinity. Following shocks showed a majority near the eastern epicenter. The strain-release curve indicates that all this activity constitutes a single event.

On March 22–25, 1956, a portable seismometer was operated by Richter and C. R. Allen at a locality southwest of the epicenter of February 9; about 40 small aftershocks were usefully recorded. The portable equipment consisted of a Houston Technical Laboratories ¼-sec vertical seismometer, a General Electric potentiometer amplifier, an Esterline-Angus ink recorder and a gasoline generator for power with radio receiver and marking chronometer for timing. This equipment performed very well under field conditions.

The temporary station was located in the zone of the Agua Blanca fault, a major feature not previously described, but studied after the earthquake by Allen and others. It is a roughly east-west fault with conspicuous right-hand strike-slip features of San Andreas type. Geographically the Agua Blanca fault is related to the fault along which the trace in February developed approximately as the Garlock fault is related to the White Wolf fault. The major earthquake of February 23, 1892, may have originated either on the Agua Blanca fault or on the one active in 1956.

Study of the arrival times of first motion by Richter and E. A. Flinn indicates that the direct wave is the first to arrive at Palomar from these shocks for distances to over 200 km.

Local Earthquake Statistics (C. F. Richter and Assistants)

Comparison of the seismicity of the area in the last few years with earlier results suggests that the Kern County aftershock activity represented approximately a temporary doubling of the general activity. The Kern County activity continues to decrease slowly, but three shocks of magnitude 4.0–4.9 and 38 of magnitude 3.0–3.9 occurred there in 1956.

Only one earthquake of magnitude over 4.9 originated in Southern California in 1956 (on November 16, west of Paso Robles, magnitude 5.0).

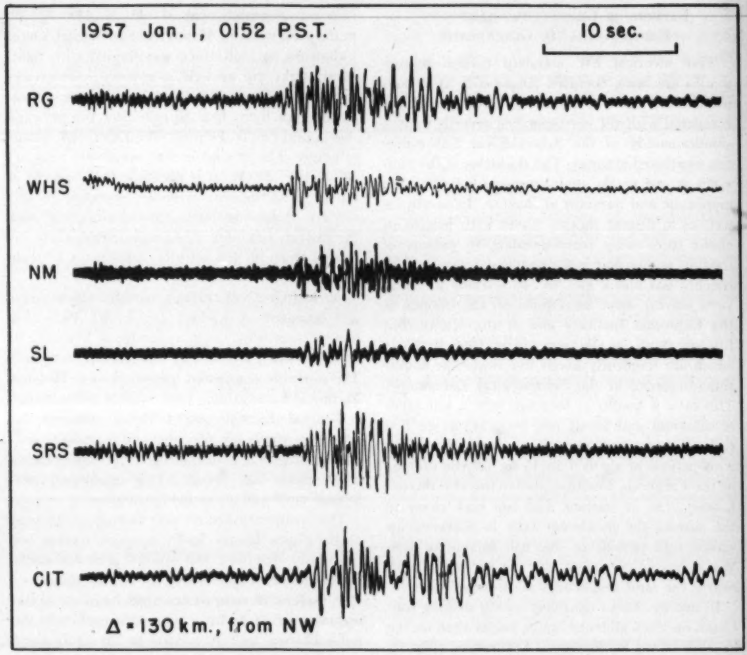

FIG. 1 – Earthquake recorded by identical EW torsion seismographs (magnification 2800, period 0.8 sec., damping 50:1) at six locations in and near Pasadena; P-waves begin near left end, S-waves near center; RG: R. Gilman residence, 416 Devirian Place; roughly 800 ft of old alluvium resting on crystalline bed rock; WHS: Washington Junior High School, on bed rock; NM: N. Motta residence, 1545 Ontario Avenue, about 800 ft south of outcrop of bed rock, thickness of alluvium roughly 100 ft; SL: Seismological Laboratory, on bed rock; SRS: San Rafael School, about 3000 feet south of SL and about 600 ft SW of Eagle Rock fault, on a few feet of alluvium over deep (> 1000 ft) Tertiary sediments; CIT: Athenaeum on campus of California Institute of Technology, thickness of alluvium roughly 900 ft

MODEL SEISMOLOGY (F. PRESS)

The effect of geologic structure on the phase velocity of surface waves was studied in an ultrasonic, two-dimensional scale model. Interest in this problem stems from the potential use of phase velocity variations as a method of geophysical exploration. It was demonstrated that thickness changes, lithology changes, faults and scarps can produce measurable variations in phase velocity of surface waves. A unique interpretation of a given phase velocity variation in terms of a particular structure is not always possible.

A two-dimensional model study of the radiation of compressional and shear waves from an impulsive strike-slip fault was carried out. The variation of amplitude, direction of motion and spectrum of the elastic pulses was studied as a function of azimuth. The behavior of the compressional wave follows geometric optic theory, giving the expected distribution of zones of compression and dilatation. Diffraction effects are pronounced for the shear wave, producing significant motion where nodes are expected on the geometric theory.

PROJECT SPONSORED BY THE GEOPHYSICS RESEARCH DIVISION OF THE AIR FORCE CAMBRIDGE RESEARCH CENTER

The project terminated on March 1, 1956, but the research of waves from earthquakes (summer months) and of microseisms (winter months) was

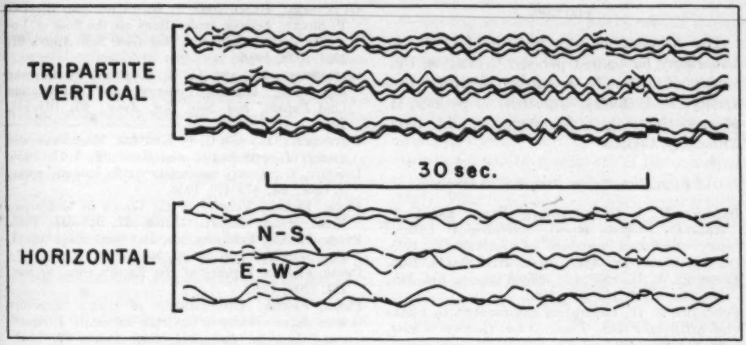

FIG. 2 – Microseisms recorded at Palomar on October 29, 1956; the upper part was written by three Benioff vertical seismographs (period one second) located on triangle with sides of about 2500 ft, the lower part by two Benioff horizontal seismographs (period two seconds); periods of all galvanometers ten seconds; in each part the first group of lines was written about 09h 05m, the second group about 10h 05m and the last group about 11h 05m

continued, awaiting the final disposition of the equipment, for which an offer has been made using funds provided by the American Petroleum Institute. The bibliography of papers on microseisms is being continued.

Microseisms with periods of about two seconds (*B. Gutenberg*)—Occasionally microseisms with periods of about two seconds are recorded in Southern California. Usually their amplitudes increase with increasing turbulence of the air, especially after passage of a cold front, and in all instances they arrived from the direction of the coast. They have a prevailing vertical component (Fig. 2) and are not visibly recorded after having traveled roughly twenty wave lengths. According to Ewing, Press and Jardetsky, such motion of *SV*-type is to be expected in surface waves of second and higher modes.

Microseisms with periods of four to eight seconds (*B. Gutenberg*)—A microseismic storm, between October 27 and November 2, 1956, was investigated in detail. Microseisms, with periods of six to eight seconds arrived, as usual, from SW to W. High pressure covered Southern California and the adjacent areas while low pressure areas moved across the Northern Pacific and into Canada. Unfortunately, some of the ocean-wave recorders which had furnished information previously are no longer in operation, but the following data have been made available. Scripps Institute of Oceanography, La Jolla: breaker height increased from about two feet in the afternoon of October 31 to about ten feet on the morning of November 1 and was reduced by mid-afternoon to 6½ feet, according to R. S. Arthur. Seaside in Monterey Bay: Sergeant Boyd of Camp Pendleton, testing an amphibious vehicle, reported that large waves began to arrive on October 30 and continued through the following two days (communicated by W. C. Thompson, U. S. Naval Postgraduate School, Monterey, California). According to R. L. Murray, U. S. Marine Corps, records at Camp Pendleton, California, indicate that deep-water waves with periods of 15 to 17 sec were between four and five feet high on October 27–29, but, during the early hours of November 1, waves caused by local fetch reached a height of six feet with periods of about 9½ sec. All these data confirm results found in previous years.

ELECTROMAGNETIC OSCILLATIONS (H. BENIOFF AND G. BODVARSSON)

Studies of the electromagnetic waves or oscillations described in our previous report are continuing. One of the problems connected with this project is the question of transparency of the ionosphere to waves in the frequency range from ½ to 2 cycles/sec. Calculations by Bodvarsson suggest that conditions for transparency for these waves may occur infrequently and, since they are observed only infrequently, the possibility exists that they may originate outside of the ionosphere. Oscillations in the frequency range ½ to $\frac{1}{10}$ cycle/sec., observed frequently during the past year, appear to be generated within the ionosphere.

Visitors

The following visitors were resident at the Laboratory for limited periods: C. Tsuboi, University of Tokyo; R. Stoneley, Cambridge University; K. E. Bullen, University of Sydney; H. Menzel, University of Hamburg; and M. Båth, University, Uppsala.

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Discussion of "Mean Airflow and Heat Transport Patterns Generated by Wind Machines with Applications to Frost Protection"

George Allen Baker, Jr.

[*Trans.*, **36**, 954–962, 1955]

Arthur S. Leonard (University of California, Davis, Calif.)—It seems necessary to make some criticism of Baker's paper because the physical problem is much more complex than indicated. Although simplifying assumptions are frequently used to good advantage in the solution of many problems, when the initial assumptions are simplified to the point where they render the final results too unrealistic for practical use, their advantage may be lost. In Baker's paper, this situation may exist.

One example of what may be a case of oversimplification is the author's assumption that the included cone-angle of the effective boundary of a stationary jet will be about 24°, and, for calculating the mass, inertia, buoyancy, and vertical acceleration of a 'slice' of the jet, this constitutes the effective boundary. Another such assumption is that the average density over the cross section thus defined is equal to the arithmetic average of the densities of all parcels of air entrained upstream of the cross section under consideration.

Actually, the outline of a submerged jet does take the general form of a cone; but there is no physical property or group of physical properties which mark the jet-boundary at all well. This particular value of cone-angle comes from *Tollmien's* [1926] work on submerged stationary jets. His equations for velocity distribution within a free jet include the concept of a fictitious boundary separating the jet from the surrounding continuum. When the values of the constants of these equations are adjusted to give the best possible fit between the mathematical model and measurements made on experimental jets, a cone-angle of 24° is obtained for this boundary. The fact that this mathematical model gives a reasonably good fit with experimental measurements over most of the flow field of the jet does not mean, however, that any physical significance should be attached to this particular boundary. For these reasons, the choice of this particular value of cone-angle for calculating the effective volume of a slice of the jet appears to be a rather arbitrary assumption.

More recent experimenters in the field of jet flow [*Albertson* and others, 1950] describe the behavior of a jet by means of equations which do not contain a radius or cone angle to indicate the relative physical size of each cross section. Instead, their equations employ the distance from the apparent apex of the cone to the cross section in question. Just as the location of Tollmien's outer boundary for the jet is determined by adjusting constants in the equations to give the best fit between theory and experiment, so also is the location of the apparent apex of the cone found. The latter equations, however, offer definite advantages because, although the effective outer boundary of the jet may be different for different effects (velocity, concentration of different components, density, buoyancy. etc.), the location of the apparent apex of the cone is relatively independent of the particular effect under consideration. Also, with these equations, the fit between theory and experiment (velocity measurements) is a little closer than with Tollmien's.

When we look into the problem of specifying the buoyancy and effective inertia in the vertical direction of a slice of the stationary jet which is operating at a small angle of inclination in a quiet body of air with a linear temperature gradient in the vertical direction, we find that it too is quite complicated. One reason for this is that in any given cross section, different individual parcels of previously entrained air will not be equally represented. A parcel of air entrained at a great distance upstream will be concentrated near the center of the cross section and will be moving through the slice at a relatively high velocity. Because of its high velocity of transport, this parcel of air will be drawn out into a thin filament and will occupy only a small fraction of the volume of the slice. Air entrained only a short distance upstream and which has a different density, on the other hand, will be spread out in the outer part of the cross section and will be moving relatively slowly. Thus it will occupy a much larger fraction of the total volume of the jet. This means that the effective density of the fluid within a slice of the jet will be something other than an arithmetic average of the densities of all parcels of air entrained upstream of the cross section.

Added to this will be the further complication brought about by the fact that air which has been entrained on the upper side of the jet will have a lower density than that entrained the same distance upstream but on the lower side of the jet. Since at any cross section mixing will not be at all complete for air entrained only a short distance upstream, the vertical density profile of any section of the jet will be unsymmetrical about the effective centerline of the jet.

Although the total vertical accelerating force which acts on a slice of the jet might be calculated, if the density distribution within the cross section were known, the effective mass (and hence the vertical acceleration) of the section might not be estimated so easily. One reason for this is that in the jet under discussion the air will be warmest near the center of each cross section. This air will receive greater vertical acceleration than the rest of the air of the jet and will tend to be deflected from the centers of succeeding cross sections. Just how much of the surrounding part of the jet will share in this maximum vertical acceleration and be carried along with it is something which cannot be predicted easily and may require experiments with this type of jet to determine reasonably accurately. Although this effect should not cause the central core of the jet to become separated from the rest, it may affect the rate of mixing within the jet.

Another assumption which is to be questioned is the author's introduction of virtual mass into his initial equations for the effective mass of the stationary jet. Virtual mass comes into play when a solid body which is completely surrounded by a fluid is accelerated relative to the fluid. When a rigid body moves through a fluid, it sets up a flow pattern around it in which the fluid velocities are directly proportional to the velocity of the body. This being the case, any change in the velocity of

the body will produce a proportional change in all flow velocities in the fluid around it. Thus, when the body is accelerated, the fluid within the flow pattern is accelerated also. The acceleration of the fluid is brought about by a pressure distribution throughout the flow pattern and which originates at the surface of the solid body. This pressure is distributed over the surface of the body in such a way that its net effect is a force against the body which adds to the inertia of the body. Thus the solid body resists the accelerating force as if its mass has been increased by an amount equal to the effective (virtual) mass of the fluid being accelerated in the flow pattern.

Even though the fluid within a stationary submerged jet may be subject to acceleration due to its buoyancy relative to the surrounding fluid, the boundary of the jet, which might be considered to behave like a solid body, is not under acceleration, in fact, it is not even moving relative to the ambient fluid. The flow within the curved outline of the jet can be likened to fluid flow within a curved conduit. Although the fluid in following the curved conduit experiences an accelerating force normal to its direction of flow, virtual mass does not enter into the problem.

The writer finds it difficult to make an accurate appraisal of many of the ideas contained in this paper because of his uncertainty about some of its details. One of the reasons for this is that many of the symbols used have not been defined in sufficient detail to make their exact meaning reasonably clear; for example, the symbol t. From the way it is used in the equations, it appears to be a time-of-travel or time-of-transport of some sort. However, no clear statement is given as to just what t is or how it might be measured experimentally. Another difficulty is encountered because some of the terminology employed, such as 'flux,' is not given specific meaning. Some of the assumptions which must have been made in setting up the initial mathematical expressions and the implications of these assumptions in terms of physical quantities have not been clearly stated. A few of the equations appear to lack dimensional homogeneity.

The author indicates that some of his final equations have been verified by experiment; but it is not clear just how he processed the raw data to be found in his references to give some of the values which he used in his equations. The writer has some experimental data which might be used to check the validity of some of the equations; but has been unable to verify them because either the meanings of some of the symbols could not be deduced, or the equations contained quantities not directly related to the experimental data.

The statement "It is an interesting conjecture that the 0.40 of Eq. (43) is in fact $\gamma - 1$ where γ is the ratio of specific heats of the gas (air)" raises the question of just how the value of the ratio of specific heats might be determined when such thermodynamic quantities as adiabatic-compressibility or heat-capacity have not been introduced into the analysis.

The author is in error in one of his references: Leonard, Arthur S., *A preliminary analysis of a turning jet*, Frost Control Project Document, Dept. of Agri. Eng., Univ. of Calif., Davis, 1953 (Unpublished). The title of the document is: Project 400 U, *A study of the efficiency of orchard heating*; and the analysis pertaining to a turning jet to which he refers has not yet been published nor entered in this Project report. Further analytical work is needed. Some of Baker's mathematical concepts might be useful if they could be made specific and the physical meaning of their implications discussed more fully.

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George Allen Baker, Jr. (University of California, Berkeley, California, author's closure)—As Leonard has pointed out, an exact solution of the problem which we have considered is fraught with many difficulties. The procedure which we adopted was to abstract from a relatively simple problem what appeared the physically most important parameter, and then to use it to develop a one-parameter theory for more complex problems. This parameter is dimensionless time, that is, the time measured in units of the rise time caused by the thermal gradient. The basic physical idea is that the wind machine shoves a blob of warm air down (and forward) into the orchard and this warm air transfers heat to the trees as long as it does not rise out of the orchard.

We wish to remark that, while our assumption regarding the boundary of the stationary jet may at first sight appear rather arbitrary, the results (Eq. 16 and 17) are independent of it, as we know physically that they must be. We remark further that if we were to consider the entire jet as bending

in the manner suggested by Leonard, there is still a virtual mass effect, even though the boundary is not in acceleration. That the virtual mass effect is still present may be seen by remembering that more air must be entrained along the outer edge of a cone with a curved centerline than along the inner edge, simply because the outer edge is longer. Straight-forward calculation shows that the virtual mass per unit volume in this case is not zero, but $\frac{1}{2}$ (tan 12°)ρ_1. The above way of looking at the problem does not seem to us to be as meaningful as considering the motion of the heat and momentum transporting, relatively better mixed central region, and assuming that the rest of the jet is built around this central region. If we cut a slice from this region, it is in motion with roughly the same forward velocity as the ambient fluid. If we transform to an instantaneous coordinate system moving with the slice, we see that this slice is receiving a vertical acceleration caused by the thermal gradient. The problem is then quite like the well-known problem of an infinite cylinder moving perpendicular to its axis. Thus the virtual mass is approximately as given in our paper.

We have, in so far as possible, used standard mathematical notation in our paper; for example, the complex variable, $z = x + iy$, denotes position in the plane of the orchard, θ denotes the polar angle measured from x towards y, etc. The one exception is in (43), where x simply denotes the dimensionless argument, and is not the same as the x used throughout the rest of the paper. From the point of view of applications, (46) is the most important and the temperature response can be calculated by means of it, given the temperature gradient, wind velocity, angular velocity of turning, and the thrust of the wind machine, for every point in its region of validity.

Corrigenda—The following corrections in the published paper are noted. Page 956, in (8), T_o^2 should be T_o; and, in (12), a should be α, and x_o should be $\dot{x}_o$; page 957, in (13), α is in units of per foot; and in the line above (16), (10) should be (12); page 959, in (33), there is a factor of $(a/b)^2$ omitted on the right-hand side; and in (34) and (36) log should be $\log_e$ or ln; and on page 960, in (45) and (46) ΔT is in °F, and in (48) $\Sigma_{m,n}$ should be $\Sigma_{m,n'}$.

Discussion of "Some Comments on the Deacon Wind Profile"

BY BEN DAVIDSON AND MORTON L. BARAD

[*Trans.*, **37**, 168–176, 1956]

Masao Shiotani (Railway Technical Research Institute, Tokyo, Japan)—The authors have made an extensive analysis dealing with the determination of parameters in the Deacon profile using wind velocity and temperature data obtained by a research group of the *Johns Hopkins University* [1953]. The opportunity for making an analysis of the same micrometeorological data presented itself during my stay in Department of Oceanography, the A. & M. College of Texas, and after my return to my present work. The following paragraphs describe the method used in my analysis and some of the results thus obtained.

In my analysis it is assumed that α and β, in the basic relation of Deacon

$$d\bar{u}/dz = \alpha z^{-\beta} \tag{7}$$

are constant with respect to height z. It is further understood that the roughness parameter z_0, appearing in the wind profile as a boundary condition of the differential equation (7), is specified by the coverage of the ground, and that a numerical value of it should remain constant throughout the air layer during the period of observation, so long as the geometrical condition of the surface of the ground is the same.

Taking the logarithm of the basic relationship (7), we obtain

$$\log d\bar{u}/dz = \log \alpha - \beta \log z \tag{8}$$

where the constant α becomes $u_*/kz_0^{1-\beta}$ by referring to the logarithmic profile under adiabatic condition. The two unknown parameters α and β are determined by the method of least squares, since $d\bar{u}/dz$ in (8) is obtained easily from the values of wind velocity at the levels of observation.

Since the levels of observation were spaced at equal intervals of logarithmic height in the original data, $d\bar{u}/dz$ is calculated as follows

$$(d\bar{u}/dz)_z = 0.434 \frac{1}{z} \frac{d\bar{u}}{d(\log z)} \approx 0.434 \frac{1}{z} \frac{\Delta u}{\Delta(\log z)}$$

where $2\Delta u = (\hat{u}_{2z} - \hat{u}_z) + (\hat{u}_z - \hat{u}_{z/2})$

and $\Delta(\log z) = \log 2.$

As we have no observed values of $\hat{u}_{2z}$ and $\hat{u}_{z/2}$ which are necessary for the calculation of Δu at the highest and lowest levels, we extrapolate the velocity profile plotted on the graph of ($\hat{u}$-log z) to the lower and higher extremes. Accordingly, it must be admitted that a small error is introduced into the calculation.

Three sets of values of α and β are calculated (a) by using wind velocities at five reference levels, namely 40, 80, 160, 320, and 640 cm; (b) by using wind velocities at four lowest reference levels, namely 40, 80, 160 and 320 cm; and (c) by using wind velocities at four highest reference levels, namely, 80, 160, 320 and 640 cm. They are denoted by (α_1 , β_1), (α_L , β_L) and (α_H , β_H) respectively.

To obtain the friction velocity u_* from α, the value of the roughness parameter z_0 is needed. The latter may be determined from the boundary condition, $\hat{u} = 0$ at $z = z_0$, in the integration of (7). An attempt was made to calculate z_0 in each set of observational data by this method. Unfortunately, it was discovered that values of z_0 were dependent on the stability of the air layer and occasionally they took on imaginary values. Accordingly, a more conventional method was adopted for the determination of z_0 from the wind profile, namely, the construction of a curve of the distribution of wind velocity under adiabatic conditions on a graph with coordinate axes $\hat{u}$ and log z. The intersection of this curve with the log z axis, was determined, and two values, 1 cm and 0.6 cm, are represented in the present analysis as the upper and lower limits of values of z_0 thus obtained. The friction velocities are denoted by u_{*1} , u_{*L} and u_{*H} respectively, corresponding to the methods (a), (b) and (c).

TABLE 7 - *Calculation of shear stress from Deacon profile*

Date	Time	u_{*1}	β_1	u_{*L}		β_L	u_{*L}		β_H	u_{*H}		Ri (z = 80)
				z_0 =			z_0 =			z_0 =		
				0.6 cm	1 cm		0.6 cm	1 cm		0.6 cm	1 cm	
	h h m	*cm/sec*		*cm/sec*	*cm/sec*		*cm/sec*	*cm/sec*		*cm/sec*	*cm/sec*	
Aug. 8	20–21 00	13.8	0.56	3.6	2.9	0.63	4.7	3.9	0.39	1.4	1.0	0.107
	22–23 00	21.9	0.75	9.9	8.7	0.77	10.1	9.0	0.71	2.4	2.1	0.029
Aug. 9	06–07 00	51.3	1.07	65.2	67.7	1.05	60.5	62.0	1.09	73.7	77.0	−0.001
Aug. 13	02–03 00	45.7	1.08	73.8	70.8	1.12	79.5	84.5	1.01	48.7	48.8	0.006
	04–05 00	45.7	0.99	43.6	43.6	1.00	45.3	45.2	0.99	43.0	42.8	0.007
	06–07 00	39.8	1.00	40.4	40.4	1.03	44.6	45.2	0.92	27.1	25.9	0.008
	08–09 00	49.7	1.10	71.2	74.8	1.10	71.6	75.2	1.10	74.6	78.5	−0.005
	11–12 00	46.8	1.12	71.1	75.5	1.09	63.5	66.5	1.17	92.5	101	−0.018
	12–13 00	47.9	1.13	73.3	78.5	1.12	70.8	75.2	1.14	83.9	90.5	−0.014
	14–15 00	52.0	1.08	70.9	74.0	1.08	75.1	78.5	1.08	73.4	76.5	−0.008
	16–17 00	53.7	1.08	62.9	65.7	1.10	68.7	72.5	1.10	68.9	72.5	−0.004
	19–20 00	16.7	0.59	4.6	3.7	0.54	3.8	3.0	0.60	4.9	4.0	0.073
	20–21 00	21.3	0.57	4.5	3.6	0.49	5.4	4.2	0.58	4.5	3.6	0.063
	21–22 00	18.5	0.62	6.1	4.9	0.61	5.8	4.8	0.58	4.2	3.8	0.046
	23–24 00	20.8	0.58	5.7	4.6	0.62	6.1	5.0	0.54	3.6	3.2	0.035
Aug. 19	00–01 00	16.2	0.68	6.0	5.1	0.69	6.1	5.2	0.63	4.6	3.8	0.055
	02–03 00	17.3	0.62	5.0	4.1	0.64	5.4	4.5	0.53	3.2	2.5	0.036
	04–05 00	20.7	0.71	7.4	6.4	0.77	9.1	8.1	0.59	3.9	3.2	0.027
	06–07 00	24.8	0.89	18.0	17.0	0.94	22.2	21.6	0.92	20.9	20.1	0.009
	08–09 00	34.1	1.15	57.5	62.3	1.17	39.6	43.2	1.15	57.9	62.5	−0.012
	10–11 00	43.3	1.14	66.7	71.6	1.17	75.1	82.2	1.13	63.6	68.0	−0.032
	12–13 00	39.8	1.18	73.0	80.0	1.20	76.8	85.0	1.19	75.5	83.2	−0.032
	14–15 00	38.0	1.19	75.6	83.2	1.18	67.3	73.3	1.24	94.9	107.2	−0.026
	16–17 00	36.4	1.16	63.4	68.8	1.18	61.7	67.2	1.19	71.2	78.5	−0.013
	18–19 00	16.7	0.76	7.5	6.5	0.75	7.1	6.3	0.71	5.9	4.9	0.026
	20–21 00	16.2	0.57	4.0	3.2	0.61	4.5	3.7	0.49	2.6	2.0	0.063
Aug. 31	06–07 00	43.3	1.02	52.5	52.0	1.08	57.3	59.6	1.02	40.4	40.8	−0.001
	13–14 00	60.1	1.14	112.5	104.8	1.13	95.1	102.0	1.19	126.1	139.0	−0.017
	14–15 00	64.7	1.13	114.5	107.2	1.13	98.7	111.0	1.15	109.4	118.0	−0.009

As a result of this analysis, it was found that the shear stress calculated by *Halstead*'s [1954] formula was in a fairly good agreement with the observed value of *Vehrencamp* [1954], and this value, $u_* = \sqrt{\frac{1}{2}}\cdot(\bar{u}_{2z} - \bar{u}_z)$, ($z$ = 40 cm), was assumed to be reliable and was denoted by u_{*z}. Now, the problem with which we are concerned here is that of comparing u_{*1}, u_{*L} or u_{*H} to u_{*z}. The difference between u_*, calculated according to Deacon profile, and u_{*z}, is supposed to represent the error of estimation.

Results of these calculations are shown in Table 7 together with the Richardson number at 80 cm. From this table, we can easily understand that the estimation of shear stress is too small under stable conditions and too large under lapse conditions. Although the change of estimated values with change of both roughness parameter and observation height is not large, it is shown that taking lower observation levels under any conditions, smaller roughness parameters under lapse conditions (and the reverse under stable conditions) brings the estimated values closer to u_{*z}.

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Vehrencamp, J. E., Studies of transfer process in the lower atmosphere, Rep. Dept. Eng., Univ. Calif., 54–28, April, 1954.

Ben Davidson (College of Engineering, New York University, University Heights, New York 53, New York) and *Morton L. Barad* (Air Force Cambridge Research Center, Cambridge, Massachusetts; Authors' closure)—We welcome Shiotani's ingenious analysis of the Johns Hopkins wind velocity data taken at the Great Plains study, but we disagree in some respects with the underlying philosophy assumed in the analysis. Although semi-empirical in nature, the Deacon profile is based on at least one assumption that stems from the equations of motion; namely, that the shearing stress is reasonably constant with height in the layer of air close to the ground [see, for example, *Sutton*, 1953, p. 79]. For the remainder, the assumptions are that the wind shear close to the ground is indeed of the form $az^{-\beta}$ where β and $a = u_*/kz_0^{1-\beta}$ are independent of height. Here $\rho u_*^2 = \tau_0$ where τ_0 is the surface stress.

The Deacon profile is thus a three parameter model, and from a purely formal point of view any or all of the parameters may vary. However, from the equations of motion, u_* is at most a very slowly varying height function in the lowest ten meters. The roughness parameter z_0 should in some way characterize the effect of the surface of the Earth on the wind profile. There is really no *a priori* reason for assuming that the effect of roughness is independent of stability, but, as pointed out by Shiotani, abandoning the assumption leads to highly erratic and unreasonable values of z_0. Accordingly, we assumed in our analysis that u_* and z_0 are independent of height and further that z_0 was independent of stability. We found then that β was a systematically varying height function.

Shiotani's analysis also assumes that z_0 is independent of height and stability; independent determinations of β and u_* are made for the two height layers. His results show that both β and u_* vary with height. His absolute values of β differ from ours, but the sense of the variation with height under stable conditions is about the same. The variation of u_* with height indicates a very rapid change of stress, ρu_*^2, with height which is not at all consistent with the equations of motion.

The upshot of both analyses seems to be that the Deacon formula, although adequate for gross wind interpolation purposes, does not accurately describe the effect of stability variations on the wind profile in the first six meters above the ground.

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Sutton, O. G., Micrometeorology, McGraw-Hill, 333 pp., 1953.

Discussion of "A Test of the Single- and Double-Ring Types of Infiltrometers"

BY R. H. BURGY AND J. N. LUTHIN

[*Trans.*, **37**, 189-192, 1956]

Leonard Schiff (U. S. Agricultural Research Service, Bakersfield, Calif.)—The use of single- and double-ring infiltrometers to determine infiltration rates is becoming widespread. Articles such as this are extremely timely. These investigators found that single-ring and double-ring infiltrometers gave about the same value on a uniform Yolo silt loam with a soil profile having no layers restricting the downward movement of water. They state "this conclusion differs from the results obtained by *Bower* and others [1951] and *Schiff* [1953] who found that the outer ring of the double-ring infiltrometer reduces lateral movement from the inner ring and thus gives a more accurate value for the infiltration rate." Burgy and Luthin "attribute this conclusion to the fact that these investigators were working on layered soils having either more compact subsoils or strata which caused an increase in the lateral flow over the vertical flow." However, the lower the permeability of the layer beneath an infiltrometer, the higher becomes the proportion of lateral flow to vertical flow. Part of such flow comes from the inner-ring infiltrometer, and the buffer becomes less effective in establishing a true infiltration rate for the inner ring. In addition, a single-ring infiltrometer may give appreciably higher infiltration rates than a double-ring infiltrometer, even in a uniform soil, if a combination of soil permeability and surface head (depth of water on the soil surface) and depth of infiltrometer in the soil result in an appreciable hydraulic gradient at the base of the single-ring infiltrometer. The hydraulic gradient for the 'falling head' single-ring infiltrometer on Yolo silt loam was undoubtedly too low to cause sufficient lateral flow at the base of the single-ring infiltrometer.

The foregoing presupposes that the objective in the field is to simulate vertical flow downward. Since infiltrometers are also used to simulate field conditions when lateral flow occurs, as in contour furrows, buffers are not desirable. In fact, the infiltrometer should be designed to permit lateral flow in a manner which simulates field conditions.

Various investigators have suggested that the Committee on Infiltration (of which the discussant is currently the Chairman.—Ed.) of the American Geophysical Union help establish standard procedures for the use of infiltrometers. This may be a worthy project for the Committee. If this were undertaken, the Chairman believes the first step would be to establish major field conditions to be simulated by infiltrometers. Another step would be to expand investigations directed toward determination of the fundamentals involved in the performance of infiltrometers. Manometers could be attached to infiltrometers at various depths in the soil to determine the magnitude of and changes in the hydraulic gradients motivating flow, noted in the 1953 paper by the writer which the authors cite. It is visualized that different standard procedures may result, a standard procedure for each set of major field conditions. *Haise* and others [1956] have made a contribution in this direction in the field of irrigation.

REFERENCE

HAISE, H. R., W. W. DONNAN, J. T. PHELAN, L. F. LAWHON, AND D G. SHOCKLEY, The use of cylinder infiltrometers to determine the intake characteristics of irrigated soils, U. S. Agr. Res. Serv. and U. S. Soil Cons. Serv., *ARS 41-7*, 10 pp., 1956.

R. H. Burgy and J. N. Luthin (Department of Irrigation, University of California, Davis, Calif.; Author's closure)—The measurement of infiltration rates is of great practical importance to agriculture and hydrology. The rational design of irrigation systems should be based on a knowledge of the rate at which water will enter the soil. Any method of measuring this rate must be simple and easily accomplished if it is to have any practical utility as a design criterion. For the special situation tested by the authors in the original paper, the single-ring infiltrometer seems to give promising results with six tests if the investigator discards the occasional high measurements. The inclusion of these high readings will result in an incorrect average and hence a poor design for the irrigation system.

Walter T. Wilson in his discussion takes issue with the idea of rejecting the extreme values and uses an analogous situation as the basis of his argument. The distribution of values obtained by the

use of an infiltrometer is one-sided. The occasional high value obtained because of the presence of gopher holes or other soil disturbance has an undue influence on the mean value. These high values must be rejected from a small sampling if the mean of the samples is to be approximately equal to a true mean. We do not intend to infer that the extremely high values obtained are in error.

Schiff's remarks are pertinent and point up some of the problems associated with the measurement of infiltration rates. Infiltrometer measurements *per se* tell us very little about the movement of water through soils and, as Schiff correctly points out, more investigations should be directed towards the determination of the fundamentals involved in the performance of infiltrometers. Since Schiff has raised the point we would like to take this opportunity to say a few words on the subject.

Apparently a theory for the use of ring infiltrometers should be based on a solution of the *Richards'* [1931] partial differential equation of soil moisture movement.

$$\partial c/\partial t = \nabla \cdot (K \nabla \theta)$$

where $\partial c/\partial t$ is the time rate of change of the soil moisture, K is the soil hydraulic conductivity and is a function of the soil moisture content and θ is the total soil-moisture potential. Strictly speaking this equation is inaccurate because it does not consider the complex physical, chemical and biological actions in the soil that result from the change in the soil-moisture content. Ignoring these reactions we are still faced with the difficult task of solving a non-linear partial differential equation. Some cases having elementary geometry have been solved [*Klute*, 1952; *Day* and *Luthin*, in press], but to the authors' knowledge no progress has been made towards the development of an adequate theory for ring infiltrometers based on solution of the Richards' equation.

Factors which are of importance in determining the amount of lateral flow that occurs in the single-ring infiltrometer include not only the effect of soil layering but also the moisture content of the soil at the time of the measurement since K is a function of that moisture content.

When an adequate theory is developed for the operation of a single-ring infiltrometer, it will then be possible to apply the results to situations having different geometry such as the seepage of water outward from a furrow into the soil. At the present stage of our knowledge any correlation between the seepage rate out of single-ring infiltrometer and a furrow must be regarded as fortuitous and not necessarily true for all soils or even the same soil at different initial moisture contents.

Lacking a suitable theory the engineer is forced to resort to the empirical approach in developing a method of measuring the important soil property known as the infiltration rate.

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Klute, Arnold, A numerical method for solving the flow equation for water in unsaturated materials, *Soil Sci.*, **73**, 105–116, 1952.

Richards, L. A., Capillary conduction of liquids through porous mediums, *Physics*, **1**, 318–333, 1931.

Letter to the Editor

Authors' Comments on Discussion of "Heated Precipitation-Gage Intake Tube"

This paper [*Trans.*, **36**, 311–314, 1955] was discussed by Richard D. Tarble, [*Trans.*, **37**, 330–331, 1956]. In this, stress is laid upon the role of heat as a possible cause of loss of the catchment by evaporation. It is true that the shelter house interior is kept at a temperature of about 45° F to maintain suitable conditions for operation of electronic equipment but as the weighing pan is enclosed and is, in addition, covered by a layer of oil a significant evaporation loss from it could not be expected at this temperature.

When external temperatures are such that capping might occur the heater operates only intermittently. It is controlled by a thermostat responsive to temperatures in the interior of the shelter house. Only the small pilot flame burns continuously. When the temperature falls enough to operate the thermostat the heater goes into action and operates until the thermostat cuts off the flow of fuel, the heater then remains inactive until the temperature again falls to the low limit of the operating range. The housing is heavily insulated to retard the outward flow of heat so that one tank of fuel can last through the winter. When the heater operates the vapor phase system extracts heat from the flue gases and transmits it to the precipitation gage intake tube to raise its temperature temporarily. When the heater is not operating the intake tube returns to a cold condition as determined by exterior temperatures. These operating characteristics are such that when capping is possible the intake tube is cold most of the time. When rain is falling and the external temperature is below 45° F, intervals between operating periods are long. When rain is falling and the external temperatures are above 45°F the heater remains inoperative.

Since the catchment either falls freely through the heated portion of the intake tube or touches it only momentarily on its way to the weighing pan no significant evaporation losses due to the intermittent heating of the intake tube should be expected when rain or wet snow is falling. When snow falls and the temperatures are well below freezing the heater operates at shorter intervals but since the heat supplied to the intake tube at each heater operation is essentially independent of the external temperature the intake tube remains colder, and again, no significant evaporation losses due to the intermittent heat supply to the intake tube are to be expected. The amount of heat supplied to the intake tube can be adjusted by means of the damper in the flue to the minimum requirement for the wet-snow condition. It is concluded that the differences in catchment between this and any other type of gage are not due to evaporation losses caused by an excessive heat supply.

Interference from updrafts from the vent should not be a significant factor in the operation of the gage because of the intermittent operation of the heater, because winds would generally deflect the flue gases away from the intake tube and because the air supply to the interior of the housing enters through a thimble which encircles the vent. The extraction of heat from the flue gases by this counter current of cold air materially reduces their temperature. These gages have served well the purposes for which they were designed. A heated precipitation gage intake tube of this type, installed in Alaska is reported to remain free of snow accumulations.

The discussion of shielding and aerodynamic characteristics, which are not the subject of the title paper, seems premature at this time. These have been made the subject of an intensive and continuing laboratory and field study by C. C. Warnick (Influence of wind on precipitation measurements at high altitudes, *Eng. Exp. Sta. Bul. 10*, University of Idaho, May 1956).

The ratio of the catchments of the radio-reporting and reconnaissance gages varies for each of the six installations, as will be brought out in forthcoming reports. This indicates that some local factor other than the heated intake or the shield is influencing the efficiency of catchment. Further thought is being given to the shape of the roof of the shelter.

Both Bureau of Reclamation and Weather Bureau hydrologists make excellent use of the radio-reported data. During the floods of December 1955, the flood-control features of the Central Valley Project functioned as planned. During this flood the peak inflow into Shasta Lake was about 200,000 cfs. At Red Bluff, about 50 mi below Shasta, uncontrollable tributary inflow into the Sacramento

accumulated to a peak flow of 110,000 cfs. Of this flow only 3000 cfs was contributed by releases from Shasta. At Ord Ferry, about 130 mi below Shasta, a maximum flow of 140,000 cfs occurred under the same conditions. Because data were available when needed it was possible to hold the heavy inflows into Shasta Lake in storage until the peak flows at downstream points had passed. Much of the flood-control benefit by Shasta Lake on the Sacramento River below Shasta Dam is attributable to the rapid transmission of reliable precipitation data from the six Sacramento Valley radio-reporting gages.

In our search of the literature we found no reference to either Weather Bureau or other investigators who experimented with heated intakes, as distinct from heated gages. We found nothing pertinent to this subject in the reference made by Tarble to Middleton and Spilhaus.

A distinction should be made between any possible evaporation losses in the heated intake section and from the receptacle holding the observed precipitation. An investigation, conducted by the Bureau of Reclamation on the evaporation losses from receptacles, concluded that transformer oil was the best of many substances tested. Practically coincidentally with the completion of this investigation, E. L. Hamilton and L. A. Andrews (Control of evaporation from rain gages by oil, *Bul. Amer. Met. Soc.*, **34**, 202–204, 1953) reported upon their independently conducted investigation, through which they likewise concluded that transformer oil was best.

The locations of the six radio-reporting gages were chosen in collaboration with representatives of the Weather Bureau. The elevations are such that rain, sleet, and snow may fall in various sequences during a single storm. The behavior of the ordinary gages under such conditions is too well-known to require detailed comment here.

The United States Patent Office has granted public patent 2,701,472, dated February 8, 1955, with certificate of correction, dated March 22, 1955, to Allen, Glover, Garstka, and Posz for the "Heated precipitation gage intake tube." Another public patent, 2,748,376, dated May 29, 1956, was granted by the U. S. Patent Office to Daum, Keummich, and Garstka for the "Electronic coding device" used in this radio-reporting system.

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Reviews, Abstracts, and Bibliography

Reviews and Abstracts

WILLARD J. PIERSON, JR., GERHARD NEUMANN, AND RICHARD W. JAMES, *Practical Methods for Observing and Forecasting Ocean Waves by Means of Wave Spectra and Statistics*, U. S. Navy Hydrographic Office Publication no. 603, +284 pp., 4 separate plates, 1955, $3.80.

This publication presents methods of forecasting and observing waves by use of wave spectra and statistics, proposed by Pierson, Neumann, and James (hereafter referred to as PNJ). It is a new approach to forecasting ocean waves, and as yet has not been used very extensively in the art of wave forecasting. The earlier and more established method for forecasting the significant waves, originally proposed by *Sverdrup* and *Munk* [1947] and later revised by *Bretschneider* [1952], has been used quite extensively in the past (hereafter referred to as SMB).

In the present review it is only logical to make a comparison between the two methods, since at some future date some type of spectrum method will probably replace the significant wave method of forecasting waves, now generally used for engineering purposes. The PNJ publication is quite comprehensive, in that it consists of nearly 300 pages and a number of enlarged forecasting curves. Much of the text, written primarily for the field man, is based on earlier technical literature by the same authors. Of the eight chapters, I, Properties of Ocean Waves, is intended to orient the field man; II, The Generation and Forcasting of Sea Waves, perhaps the most important chapter in the text, represents the foundation on which is based the PNJ method; III, Wave Propagation and Forecasting Swell Waves, makes use of filtering techniques, but depends critically on the fundamentals of Chapter II; IV, Synoptic Forecasting Methods and Weather Analysis, illustrates the mechanics of II and III as applied to various meteorological situations; V, Wave Observations, gives recommended techniques for observing and tabular recording of waves in the open sea; VI, Wave Refraction, illustrates methods for refracting components of wave trains; VII, Operational Application of Forecasting Methods, discusses the use of forecasts and some effects of waves on ship and seaplane motion; and VIII, Verification by Forecasts and Observations, illustrates procedures used for verifying forecasts with observations, the intention being to perfect one's technique in the art of forecasting.

It is not the intention of this reviewer to go into detail on any of the above chapters. Instead, a particular review is made of PNJ method, compared with SMB method. PNJ make use of the semi-theoretical spectrum proposed by *Neumann* [1953] and the theoretical distribution function given by *Longuet-Higgins* [1952]. SMB make use of semi-empirical relationships for the significant waves and the empirical distribution function of *Putz* [1950]. Although the work of Putz came nearly two years prior to that of Longuet-Higgins, the two distribution functions for wave height variability give almost identical results. In addition, *Putz* [1952] gives a distribution function for wave period variability. One finds that if PNJ and SMB give the same significant wave height H_s, then one obtains almost exactly the same wave-height distribution, the same average wave height, the same average of the highest ten per cent of waves, etc.

In regard to the wave period, SMB makes use of the Putz distribution on wave-period variability, whereas PNJ predicts the average wave period and the wave period associated with the maximum wave energy. By definition of the significant wave period one should expect it to be in close agreement with the PNJ forecast of the period associated with maximum wave energy. In either method one should expect fairly close agreement in wave forecasts, since both PNJ and SMB methods are based on actual wave observations. However, agreement is not always reached between the two methods.

One of the reasons for non-agreement is probably because not all the same observed wave data have been used for establishing the forecasting relationships of the two methods. In addition, the data used in both methods have not been analyzed by the same techniques. However, this is not the complete story. The greatest difference between the two methods results from the spectrum proposed by *Neumann* [1953]. Neumann arrives at a relationship for a fully arisen sea of H proportional to $V^{5/2}$, where H is wave height and V is wind speed; SMB utilized H proportional to V^2 for a fully arisen sea. Consequently, PNJ predicts lower wave heights at low wind speeds and higher wave heights at high wind speeds. In fact, if one multiplies the wave heights for a fully arisen sea obtained by PNJ by $\sqrt{27.4/V}$ where V is wind speed in knots, one obtains exactly the wave heights predicted by SMB and conversely if one multiplies SMB heights by $\sqrt{V/27.4}$ one obtains exactly the PNJ heights. For wind speeds between 20 and 35 knots (where the ratio $\sqrt{27.4/V}$ is nearly one) essentially the same heights are obtained regardless of method used. For this reason the two methods cannot easily be checked one against the other for wind speeds in this range.

The question then arises, is the wave spectrum proposed by Neumann in error, or are the relationships proposed by SMB in error? It might be mentioned here that *Darbyshire* [1952] finds for his wave spectrum for waves in intermediate to shallow water $H \sim V^{3/2}$. In a later paper *Darbyshire* [1955] finds for his spectrum in deep water that $H \sim V^2$.

It is important here to make an attempt to determine whether the wave height in a fully arisen sea is actually proportional to the $\frac{3}{2}$, $\frac{5}{2}$, or $\frac{2}{1}$ power of the wind speed. All relationships for wave generation in a young sea and also the relationships for decay of swell depend also on the correct representation of wave generation. It is the belief of this reviewer that the wave height for a fully arisen sea is proportional to the square of the wind speed as shown by *Darbyshire* [1955] and others [*Sverdrup* and *Munk*, 1947; *Johnson*, 1950; *Bretschneider*, 1952] (and not the $\frac{5}{2}$ power), except for very high (steep)

waves wherein non-linearity enters the problem and the wave height is probably proportional to a power less than 2 depending on the degree of non-linearity. By use of Buckingham's [1914] π theorem and dimensional analysis one can show that the wave height for a fully arisen sea should be proportional to the square of the wind speed. This has been done by *Johnson* [1950] and probably others.

In the development of the wave spectrum *Neumann* [1953] gives the relationship

$$H = \text{const}\,\frac{g\bar{T}^2}{2\pi}\,e^{-(g\bar{T}/2\pi V)^2} \qquad (1)$$

the envelope of observed data, where H = wave height, g = acceleration of gravity, $\bar{T}$ = apparent wave period, and V = wind speed.

This equation is a very significant establishment, since it represents the first step in obtaining the wave spectrum. Eq. (6) through (11) of *Neumann* [1953] give the development of the wave spectrum. Note in this development that division by ΔT is made for expressions resulting in the left-hand side of (11), and as $\Delta T \to 0$ one cannot permit loss of the dimensions of T. The right-hand side is not operated on. The integration of (11), energy with respect to time, might result in units proportional to wave power. A constant C with the dimension of sec^{-1} is introduced to give the equation dimensional homogeneity; that is, to regain the loss of the dimensions of T as $\Delta T \to 0$.

It is this reviewer's belief that this is not proper. Unless the constant has physical significance it cannot arbitrarily be assigned any dimension. The original Eq. (1) above is completely dimensionless, and the constant cannot therefore have physical significance but must remain dimensionless. It is realized that in many cases in the past common practice has sometimes interchanged energy and power. Although this might be a convenient means to an end, it is, nevertheless, an incorrect practice, particularly in regard to the characteristics of ocean waves. It is therefore the belief of this reviewer that the Neumann spectrum is proportional to wave power and not wave energy, although (1) above is basically correct. It can be shown that the wave power is proportional to H^2T, and, by use of π theorem, proportional to the fifth power of the wind speed. Equating the power spectrum to the wave energy (proportional to H^2) results erroneously in H proportional to the $\frac{5}{2}$ power of the wind speed.

Since it is the reviewer's belief that the wave height in a fully arisen sea is proportional to the square of the wind speed, a reanalysis has been made of the data presented by *Neuman* [1953, 3, Fig. 8]. Based on SMB relations for $gH_s/V^2 = 0.26$, one finds as good a

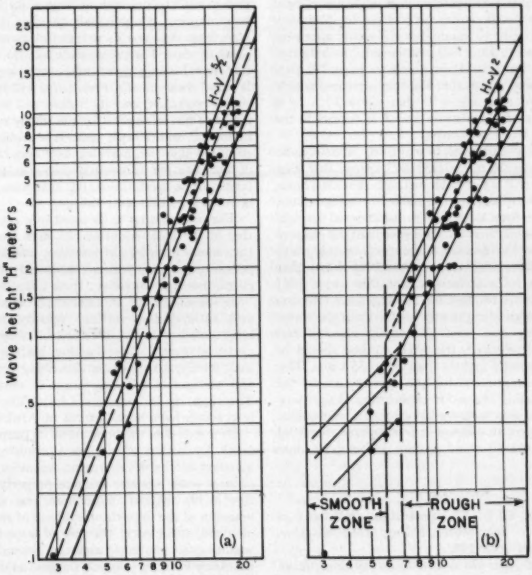

FIG. 1 – Wave height observations at different wind speeds (a) after Neumann; (b) interpretation by Bretschneider

fit for $H \sim V^2$ as for $H \sim V^{5/2}$. (See Figure 1 for reviewer's interpretation of these data). In fact if one neglects the lowest value of $H = 0.1$ m. for V_{-10} = 3 m/sec, one finds a much better agreement for $H \sim V^2$ than for $H \sim V^{5/2}$. The use of this one value may be questioned for two reasons: (1) the wind speed is definitely below critical wind speed, and (2) such a low value of H versus V should be used with caution for predicting waves at high wind speeds. The first reason finds many arguments between oceanographers as to whether there actually exists the so-called smooth and rough zone, a subject of which is too vast to include in this review. The second reason is definitely in agreement with sound engineering practices.

It is this reviewer's belief that until oceanographers decide on the behavior of the critical zone, all wave data for wind speeds below 6 to 7 m/sec should be neglected when predicting waves for higher wind speeds. This being the case, the reviewer reanalyzed the data for wind speeds above 7 m/sec from Figure 8 of *Neumann* [1953] to obtain the best-fit least-square relationships. From the regression of log H on log V a slope of 1.88 was obtained for the upper limit and 2.12 for the lower limit of the data, and from the regression of log V on log H a slope of 2.09 was obtained for the upper limit 2.35 for the lower limit of the data. The above may not be a fair analysis since all the original data were not on hand. However, it is sufficiently convincing that the data of Neumann agree better for $H \sim V^2$ (as utilized by SMB) than for $H \sim V^{5/2}$ (as utilized by Neumann and PNJ). Actually Neumann himself would appear as yet uncertain as to the exact relationship, as indicated by *Cox* and *Munk* [1954] in which on page 222 they quote, "Neumann states that his data are convincingly better in accord with $T_T \sim T^4$ than T^3 or T^5." T_T is related to the period spectrum and T is related to the first power of V.

It is difficult at this point to make any recommendations in regard to the use of H.O. 603, except that forecasts using either PNJ or SMB methods should be made by or under the direction of qualified oceanographers. An expert wave-forecaster should obtain good verification using either method for wind speeds in the range of 20 to 35 knots. Verification of forecasts in this range does not constitute verification of the PNJ theory that $H \sim V^{5/2}$ for a fully arisen sea. For this reason PNJ method should not be used for making wave forecasts for wind speeds greater than 35 knots. Until the wave-spectrum theory has been thoroughly checked and modified where required, the SMB method should be used for wind speeds greater than 30 to 35 knots. This is particularly important for the special case of the maximum probable wave for engineering design purposes. Now that this reviewer has created a controversy or at least revived an old one, it is suggested that PNJ and SMB get together and resolve this problem once and for all.

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C. L. Bretschneider

Sverre Petterssen, *Weather Analysis and Forecasting*, 2nd ed., vol. 1, *Motion and Motion Systems*, McGraw Hill, 428 pp., 1956, $8.50.

Petterssen has set himself the goal of relating the theory and the practice of large scale meteorology; his two volumes, of which only the first is reviewed here, have been designed as a text for instruction from this point of view. For the past decade the need for such a text has become more and more apparent, so that *Weather Analysis and Forecasting* will receive an enthusiastic reception, and its author will win the deserved praise of his colleagues for the timely completion of an important and difficult task. It is probably fair and accurate to say that, marking as it does the incorporation of quantitative theoretical ideas in forecasting, this book will be recognized as a milestone in the development of scientific meteorology.

The first chapter is devoted to a compact presentation of the basic equations of large scale meteorology, then come in order: kinematics, relation of wind and pressure, friction, vertical structure of wind systems, circulation and vorticity, three chapters on motion of 'long waves,' fronts, structure and behavior of cyclones and anticyclones, vertical velocity and divergence, large scale instability, development of cyclones and anticyclones, numerical forecasting, graphical integrations, and, finally, an appendix describing vector operations, and methods for computation of various quantities. The chapters on large-scale instability and numerical forecasting have been written by Arnt Eliassen.

How well does the book fulfill its purpose as a general text? An author who aims at comprehensive understanding of the development, behavior, and structure of large scale pressure systems properly must be selective in his material. Therefore, one may accept the omission of the important subjects of radiation, change of phase, turbulence, the role of boundary conditions, smaller scale motions, and the general circulation as necessary in order to reach the goal as directly as possible. However, the goal is not approached directly. It is disappointing, after reading through the necessary material on basic equations, to be confronted with a presentation of the tedious and rather unimportant

subject of kinematic relationships. Again, after the presentation of the basic physics and mathematics of circulation and vorticity, the reader is faced with 47 pages on the linearized barotropic wave. Now, however central a position the linearized barotropic wave occupies in the history of meteorology, it exists only as an interesting and instructive concept, so that elaboration of details of assumptions or of methods of applying theory to observations is not justified. The felony is compounded later on with the cavalier dismissal of J. G. Charney's seminal work on baroclinic instability, namely, "Since his derivations were based upon the method of small perturbations, his results need not necessarily apply to mature cyclones" (p. 301). But what is sauce for the goose is sauce for the gander; the perturbation method is a systematic linearization of the equations, and in this case is far more general than is the treatment of the barotropic wave. The 55 pages devoted to fronts and the idealized relation of fronts to structure of weather systems confuses rather than clarifies the development of a quantitative and comprehensive understanding of large scale weather. If "the essential features and processes suggested by J. Bjerknes in 1918 have withstood the wear of time" (p. 217), how must one accept the main burden of the book which clearly goes far beyond and in part contradicts this view? Some of the earliest work which charted the new direction was performed by J. Bjerknes, himself. Surely there is now adequate evidence that cyclones may develop independently of an unstable wave on a pre-existing frontal surface and that the fundamental element in cyclone development is the potential energy of the distribution of mass summed through the depth of the troposphere.

Happily, the last third of the book refocuses on the problem of a comprehensive description and understanding of cyclones and anticyclones. For the most part, the material presented here is important; it is logically organized, and clearly presented. It is pleasing to see a chapter devoted to instability theories, although the attention devoted to this important subject is severely limited; and the essential concepts of baroclinic instability have not been incorporated in the rest of the book. One wishes this were different. The chapter on development of cyclones and anticyclones (based on Sutcliffe's well-known paper on the subject) properly may be considered the focal chapter for the whole book. This chapter is followed by excellent accounts of cyclone development, and then by brief but clear presentations of numerical forecasting and graphical integration.

These chapters bring the reader to the summit toward which the author has been guiding him. Undoubtedly, the most important fact to a climber at the top of a mountain is the fact that he has arrived. His guide has been successful and, in the main, correct in his trail breaking. Petterssen's main objective has been achieved. One may, however, entertain doubts as to whether the excursions through various thickets and down several old and rutted trails were always the best way to the summit.

The book seems to be directed toward a wide audience; nothing beyond the elements of physics and the calculus are assumed; and meteorological subjects are developed from the most elementary concepts and principles. However, advanced subjects are occasionally referred to before they are introduced systematically, so that it will be difficult for a beginning student, however capable, to use this book efficiently. More serious for the beginning student, however, are the occasional ambiguities or misimpressions which appear in the elementary material. For example, adiabatic and isentropic processes are treated as though they were identical, signs of the terms 'advection' and 'gradient' are each reversed on at least one occasion, the Brunt-Douglas isallobaric wind is treated without serious qualification, the statement is made that movement of a cyclone in the direction of the isallobaric gradient *will occur* (instead of *has occurred*). For readers with a sound background in theory these matters are not serious, but for many students they may be. And, for every reader, rough spots of this sort inevitably weaken his confidence in the development and the conclusions reached in the more advanced topics.

Therefore, one can, in good conscience, recommend this book only to those students who possess a sturdy knowledge of the elements of hydrodynamics and theoretical meteorology. For these students, the elementary material well might have been omitted.

Research in meteorology differs from research in physics or many branches of applied mathematics in that so many important subjects in meteorology must be evaluated more or less indirectly. This makes meteorology a playground for the lazy or the partly trained. This, in turn, places an unusual degree of responsibility on an author of a meteorological text for critical evaluation of his material. Here is the deficiency which underlies the weaknesses already referred to in this review; the subject matter is treated without evaluation, so that the completed book comprises a long series of topics, some important, some unimportant, some accurate, some less accurate. This makes large scale meteorology appear to be even more difficult than it is.

There are only few typographical errors, the figures are excellently designed and drafted, and the production of the book is up to the publisher's usual high standard.

Petterssen deserves the sincere respect and gratitude of meteorologist and other geophysicists for writing, at this time of scientific development and changing viewpoint, a comprehensive account of large scale atmospheric motions. Only one who has written a comparable book, and there is none, properly can afford to be unappreciative of the accomplishment or unsympathetic toward the weaknesses of this book. *Weather Analysis and Forecasting* fills a large gap in meteorological literature; it is a valuable book.

R. G. FLEAGLE

HOYT, WILLIAM G., AND WALTER B. LANGBEIN, *Floods*, Princeton University Press, 469 pp., 1955; $7.50.

This book holds much for many people—hydrologists and flood-control engineers; legislators and government executive officers, federal, state or local, who have flood problems with which to contend; and the intelligent lay reader who likes to be well informed.

For the hydrologist and flood-control engineer, perhaps the most useful portion is chapter 9—comprising nearly half of the book—entitled "Basin Problems, Projects, and Plans" which gives a splendid resume of the plans for flood control and mitigation for the whole country, region by region, either completed or projected, and problems yet to be faced. The outline and development of our national flood-control policy and its relations to our basic law, the Constitution, is perhaps

next of importance to the hydrologic engineer. The earlier chapters, dealing, in large measure, with the hydrologic problem is for the most part intended for the intelligent lay reader and the legislator.

The book correctly emphasizes that flood control is at best flood mitigation, not flood elimination, and that it may lead to a sense of false security. It emphasizes the important role of zoning in damage mitigation—a phase not sufficiently developed in the past. When flood control has once been instituted there has been, too often, the belief that the flood hazard has been eliminated and, as an unfortunate consequence, flood plains have been more completely developed with the result that even greater damage will occur in the event of the flood of a millenium. The paradox is pointed out that frequent floods tend to eliminate the flood-control problem while infrequent floods tend to accentuate it.

The authors develop the thesis that local participation in flood control is desirable, and that the recent tendency for flood control to be almost entirely in federal hands is perhaps not for the best. Participation by local interests develops a sense of civic pride, community interest, and watchfulness that are indeed to be encouraged. One might point out that the myth (and myth it must be) of the little Dutch boy with his finger in a hole in a dike could hardly have been born without such civic interest.

The well-prepared chapter entitled "Man's Adaptation to Floods" includes an important section explaining the background and philosophy of flood insurance, now about to become a reality on a large scale.

The book, while a masterly presentation in an overall sense, is not without minor omissions and shortcomings. The title is somewhat of a misnomer; it might more appropriately be called *Floods in the United States*, as more than 90 per cent of its contents relates to such floods.

It mentions only incidentally two other important types of floods, neither of which relate particularly to inland waters which are the concern of this book. These are seismic sea waves or tsunamis and the floods caused by storm surges (including seiches) such as inundated large areas of Holland and other coastal areas of the North Sea a few years ago and also accompany hurricanes moving inland.

The authors note that floods originate on the land and that the general effect of reservoirs is to mitigate floods. The effects of operations on the land in relation to flood control have been frequently overstated. In general, this book places these effects in proper perspective. As long as there is a reservoir within the land that is not filled (that is, as long as the field-moisture capacity is not satisfied) the filling of this reservoir will help to lessen the flood in areas for some short distance down stream. What one can do to aid in the more effective use of the reservoir by operations on the land is all to the good. For the extreme flood, caused by long duration of rainfall, especially in large basins, the effect is nil, but for the minor floods just overtopping the flood plain and causing much damage and loss to crops on fertile bottom land (a frequent occurrence in summer when the field moisture requirements of the lands of the watershed are not fully satisfied), increasing the opportunity for filling the reservoir in the land will be helpful in reducing the peakflow, and in the aggregate over the years, the benefits may be very substantial.

The argument regarding large versus small reservoirs is well presented, and the statement that remoteness of the reservoir from the point to be protected decreases its effectiveness greatly is well developed. The reviewer feels, however, that the implication that releases from a reservoir (through flood-control operations) might have an adverse effect, say, two days or more of travel distance downstream, might be stronger.

There are a number of confusing passages—perhaps more confusing to the non-technical reader than the hydrologist. The sentence closing page 29 and opening page 30 is a case in point. Another is the statement on page 13: "Rivers would continue to flow in rock-bound channels throughout their length and history, were it not for the effect of curvature." This seems to indicate that there would be no erosion and no deltas, and that subsidence or uplifting would be without effect on the behavior of the stream.

One correction: Robert E. Horton died April 22, 1945, not in 1946 as reported on page 296.

The typography is generally excellent. One minor blunder occurs in the presentation of the figure on page 198. Elsewhere there is lack of consistency in the presentation of figures, for example, pages 60 and 322. Figure 26 on page 87 is an example of correct orientation.

WALDO E. SMITH

EDWARD ROWE SNOW, *The Vengeful Sea*, Dodd, Mead, xi + 307 pp., 16 ill., 1956, $4.00.

Man's attempt to navigate the oceans is frequently complicated by unfavorable meteorological and oceanographic factors. Lugubrious tales of the shipwrecks that result in such conditions were popular reading a century and a half ago. In this informative volume, Snow has rewritten the more famous of these accounts and added some from more recent time (as recent as the stranding of the *Etrusco* on Cape Cod in March 1956).

J. L.

Abstracts of the papers presented at the Pacific Northwest Regional Meeting, Seattle, Washington, November 8–9, 1956, listed in the order of the last names of the first author

CLIFFORD A. BARNES (University of Washington, Seattle, Washington) *Tidal Currents and Dispersal of Fresh Water in Puget Sound and Environs*. Puget Sound is characterized by a surface layer of brackish water feeding seaward under the influence of hydrostatic head. This layer is being continuously replenished by fresh water from precipitation and runoff, and by salt water entrained from deeper layers. Although the net movement is outward at the surface and inward at depth, the predominant movements are oscillating in response to the tide. Fresh water accumulates to a spring maximum in March or April, a build-up from the excess

precipitation and runoff of winter, and to an annual peak in June reflecting an added contribution of melting snow from the higher watersheds. The concentration of fresh water is at a minimum during August and September, not only as a result of decreased precipitation and runoff, but also due to displacement by an influx from the sea of the year's most saline water. Some of the local concentration anomalies and methods of measuring concentration are discussed.

HOWARD F. BATES, HAROLD R. VINYARD, AND FRED W. DECKER (Dept. of Physics, Oregon State College, Corvallis, Ore.) *Correlation of Microseism Amplitude at Corvallis, Oregon with Components of Atmospheric Pressure Gradient.* The amplitude of microseisms observed at Corvallis, Oregon, was correlated with the magnitude of the sea-level atmospheric pressure-gradient components given by pressure differences in Oregon between Portland and Roseburg along a nearly north-south axis and between Astoria and The Dalles along a nearly east-west axis. Positive values of Roseburg minus Portland pressures ('northward' component) showed a positive 0.608 coefficient of correlation, whereas the southward component showed a low positive correlation. Both the eastward and westward components showed low negative correlation. These results would fit the hypothesis that the microseisms are in some way related to the speed of the west wind component, since this component of the wind is directly proportional to the northward component of the pressure gradient.

RANDALL E. BROWN (Hanford Laboratories Operation, General Electric Co., Richland, Wash.) *Determination of the Geological Conditions at Hanford Regulating the Ground Disposal of Radioactive Liquid Wastes.* Hanford's success in safe, economical waste disposal depends on unusual geologic and hydrologic conditions and on their proper evaluation and utilization. The formations contacting the wastes include the Pleistocene Ringold formation, the Palouse soil and post-glacial fluviatile sediments. Inadequate exposures require extensive well drilling to define the structure and stratigraphy. Beds are traced by drillers' logs, megascopic and microscopic comparisons of samples, particle size-distribution studies, clay mineral and ion-exchange capacity comparisons. Geologic controls of ground-water movement are indicated by regional water-table level studies, well hydrograms, tracer tests, in-well velocity tests, aquifer-performance tests, the observed behavior of ground-water contaminants, the seasonal effects of the Columbia River on the water table, and the effect of discharge to ground of large volumes of non-radioactive cooling water. Mathematical and laboratory studies validate the field data. Use of these techniques permitted the determination of the detailed stratigraphy beneath the project, proved the deformation of the Ringold formation and its significance, outlined the permeabilities and transmisibilities of the respective units, and resulted in a vastly expanded disposal program with correspondingly increased economy and a high degree of radiological safety.

JAMES J. FUQUAY (General Electric Co., Richland, Wash.) *Field Studies of Diffusion, 200 Meter Scale.* Relatively high short-period dosages are found when material is released from a ground source during various meteorological conditions. Experiments are described in which fluorescent material is dispersed from a ground source. The distribution of short-period concentrations as related to longer-period averages observed during several field tests are presented. Relationships between dispersion patterns and some meteorological variables are investigated.

PHILIP A. GOLDBERG (Boeing Airplane Co., Seattle, Wash.) *Natural Electromagnetic Activity at Low Audio and Subaudio Frequencies.* Natural electromagnetic fields with frequencies in the one to 150 *c/s* band were observed in eastern Oregon with induction-loop systems. Most of the fluctuations detected (between 30 and 150 *c/s*) are due to slow-tail-type radiation from distant lightning. A regular diurnal variation with prominent structural features points to origins in major storm centers (South America, central Africa, and southeast Asia). A strong midafternoon maximum reveals features of propagation different from those found for *r-f* atmospherics. The paper discusses the effect of the *D* layer with its relatively high conductivity at these low frequencies. A correlation is noted that involves activity of the ionospheric *F*-2 region and fluctuations of this type, as well as those slow enough to actuate conventional magnetic variometers. Extensions of the experiments are suggested for observing fluctuations in lower ionospheric parameters.

A. E. HARRISON (University of Washington, Seattle, Wash.) *Multiple Glaciation Since the Ice Age.* Evidence of moraines indicating two distinct, earlier glacial advances, comparable in magnitude to the glacial activity during the last 400 years, has been found by stereoscopic examination of aerial photographs of the Sierra Nevada Range in California. Several of these moraines have been examined in the field. The moraines are tentatively dated as more than 400 years old and of Cochrane age or younger. The consistent appearance of these older moraines in the Sierra Nevada cirques, and the lack of reports of an equivalent to the Cochrane, Ontario readvance of the Wisconsin Glaciation in California, suggests that this area would yield valuable information on late-Wisconsin and post-Wisconsin climatic conditions.

GERHARD KLEIN, RICHARD G. ORCUTT, AND WARREN J. KAUFMAN (Sanitary Engineering Research Laboratory, University of California, Berkeley) *Ion-Exchange and Hydraulic Phenomena in the Underground Movement of Radioactive Wastes.* The study was prompted by the enormous potential storage capacity of underground disposal sites and the favorable economic aspects of direct disposal into the ground. The possibility of injection into connate-water bearing formations is considered. For the design of an efficient and safe disposal system, a knowledge of the factors contributing to the dispersion of concentration fronts is necessary along with a knowledge of geologic and hydrologic aspects. The front of a solution entering the ground becomes progressively disperse owing to (a) fluid velocity variations and (b) retardation of certain cations by ion-exchange. Front dispersion due to velocity variations was examined theoretically, leading to an expression analogous to that for molecular diffusion $C = \frac{1}{2}\{1 - \operatorname{erf}[(1 - V/V_0)/2\sqrt{(D/L\bar{v})(V/V_0)}]\}$ where C is the effluent concentration relative to the influent concentration of a solute not undergoing ion-exchange, V is the

effluent volume, V_0 the voids volume, D the 'coefficient of dispersion,' an empirical constant, L the length of travel, and $\bar{v}$ the average flow velocity. This equation was checked in the laboratory with sand columns and solutions of sodium chloride. Good agreement was found for a variety of conditions. For the materials studied, D was found to be proportional to $\bar{v}$, independent of L, and characteristic of the porous medium at any value of $\bar{v}$.

For ion-exchange, the theory of Hiester and Vermeulen [*Chem. Eng. Progress*, **48**, 505, 1952] was used. The breakthrough of strontium was primarily studied since radiostrontium constitutes one of the most hazardous, abundant, and long-lived components of fission-products wastes. The porous media examined included California oil sands saturated with brine. The most important parameters affecting breakthrough were studied, including pH, exchange capacity, equilibrium constants for ion-exchange, flow-rate and distance of travel. Increased pH caused an increase in the exchange capacity of one California sand and a halloysite, as well as an increase in the partial exchange capacity for strontium in the presence of calcium. The media studied although exhibiting exchange capacity values ranging from 0 to 26 meq per 100 g, showed very little variation of the equilibrium constant for the exchange of calcium and strontium, which slightly favored the adsorption of the latter. The general rate coefficient increased with flow-rate but remained constant for varying column length. The experimental findings were correlated with theoretical breakthrough curves.

PAUL E. LEMMON (Soil Conservation Service, Portland, Ore.) *The Spherical Densiometer for Estimating Forest Overstory Density*. The spherical densiometer is a practical and reliable pocket-type instrument to obtain comparative information about forest overstory density. It measures the relative amount of light cut off by specific areas of the forest overstory from any point near the forest floor. The instrument is equally useful to scientists doing highly technical research or to foresters, range conservationists and plant ecologists applying their scientific knowledge to practical problems. The instrument uses the principle of a curved (spherical) mirror to reflect the overstory condition at a point and make possible the estimation of relative amounts of area covered and not covered. Estimations are made of the reflected overstory by means of a grid. Two models of the spherical densiometer have been standardized. One uses a convex mirror with the desired grid scratched on the surface. The other uses a concave mirror with an estimated grid superimposed between it and the eye of the operator. Trials by different operators with both types of instrument have shown that there is no significant difference among measurements of overstory density made by different operators or with different instruments. Differences in forest overstory density, however, are measured with an unusually high degree of fidelity. Average measurements of the same overstory area can be expected to be within ± 1.3, ± 2.4 and ± 3.1 pct at probability levels of 70, 95, and 99 pct respectively. These represent variation coefficients of about 2, 3, and 4 per cent.

IURY L. MAYTIN AND E. ROY TINNEY (Washington State College, Pullman, Wash.) *The Effect of Logging on the Runoff of a Stream Near the Columbia River Estuary*. A study of the logging records and the available data on the precipitation and runoff of the Naselle River near the estuary of the Columbia River. No significant influence on the runoff due to logging was detected, even though 63 pct of this watershed has been logged in the past quarter of a century. It is held that a rapid regrowth of the area, due to moderate temperatures and heavy rain-fall, is the chief reason for the lack of influence of logging, since only a very small extent of the total area is denuded at any one time.

GREGORY L. PEARSON (Soil Conservation Service, Salt Lake City, Utah) *Determining Practical Snow Course Consistencies*. Snow-course records are analyzed to determine, first, the consistency of individual samples as related to the course average, and second, the number of samples required per snow course to assure an acceptable measure of the snowpack water content. Factors which cause inconsistent records are noted. The need for more analysis of basic snow-course records and published data before making hydrometeorological studies is stressed.

MAURICE RATTRAY, JR. (University of Washington, Seattle, Wash.) *Salt-Water Intrusion Pertaining Especially to Lake Washington*. Salt-water intrusion into fresh water occurs at the junction between fresh- and salt-water systems because of the hydrostatic pressure difference caused by the density difference of the two water masses. The mechanics of intrusion are discussed using examples from Lake Washington to estimate the rate of salt inflow. Salt-water may be flushed out of a fresh water system either by the annual density turnover or by entrainment in a superficial fresh-water outflow. Methods for estimating the occurrence and amount of this flushing are applied to the Lake Washington system.

J. R. RAYMOND AND W. H. BIERSCHENK (General Electric Co., Richland, Wash.) *Hydrologic Investigations at Hanford*. During the twelve-year history of the Hanford Plant, several hundred wells have been drilled in order to obtain hydrologic, geologic, and radiologic monitoring data. Hydrologic data obtained throughout the Hanford site show that due to discharge to ground of about 28 billion gallons of non-radioactive process cooling water, the water table has locally been raised approximately 80 ft and that 20 miles southeast of the disposal sites it has been raised 0.5 ft. Pumping-test data indicate that locally the underlying aquifers may transmit as little as 30,000 gpd/ft and as much as 3,000,000 gpd/ft. Such hydrologic and hydraulic data are used to assist evaluation of safe radioactive waste disposal practices and to estimate effects of large volume non-radioactive process cooling water disposal.

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Notes and Personalia

Notes

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RECENT DEVELOPMENTS IN IGY—All phases of the work of the International Geophysical Year, looking forward to its formal initiation on the first of July, 1957, have been making rapid progress. Because of the advent of the Antarctic winter, plans there are largely complete. Parties have moved into the Antarctic continent and have already begun their work. Australia announced that the *Kista Dan* reached the Australian base at Mawson on February 2. The French ship *Norsel* arrived at Dumont d'Urville on the Ile des Pétrels on December 23. This is the second French expedition which has a wintering party of twenty men with a secondary base at Charcot with a wintering party of three men. The British party which will be stationed at Halley Bay arrived on the *Magga Dan* on February 12 with a party of 21. Other British bases will be located at Shackleton, Port Stanley, South Georgia, Admiralty Bay, Port Lockroy, Hope Bay, Horseshoe Island, Duse Bay, Loubet Coast, Deception Island, and Signy Island. Equipment at all these bases is being installed and will be ready for operation on July 1.

The Japanese expedition, under the scientific leadership of Nagata, arrived on the *Soya Maru* off Hongul Island in January 25. The base is at Lützow Holm Bay and will be known as Showa Base. The Scott Base of New Zealand at Pram Point on the east side of McMurdo Sound is now about complete under the leadership of Edmund Hillary. The base at Adare Station is a cooperative United States - New Zealand enterprise; and three New Zealand scientists stationed there will be responsible for the scientific work, excepting the meteorological program, which will be entirely under the United States. The six U. S. stations (including the Adare Station) are now largely complete with a total complement of 62 scientists and 202 in support. The establishment of the Wilkes Station with ten scientists and 17 in support is soon to be undertaken and is perhaps complete by the time this report is published. The stations of the USSR are now complete and are making final preparation of the formal scientific work.

In addition to the preparations to undertake the active scientific work during these preliminary stages, reconnaissance flights and trips are being made that will enable the final detailed planning of the operations.

The Society of American Bacteriologists has presented a project for a microbiological survey of the Antarctic to be undertaken in connection with IGY work. This has been approved by the U. S. National Committee even though it is non-geophysical in its character. It is felt that it offers prospects of providing very important and significant information concerning the Antarctic.

Plans in the Arctic are developing more rapidly now in preparation for the Arctic summer. The United States plans include the maintenance of 38 observing stations in the Far North and there will be somewhat over 200 Arctic observing stations set up by ten cooperating nations. We are already getting, as a matter of routine, much information on meteorology and the upper atmosphere in Arctic areas.

Of the U. S. stations, 21 are located in Alaska and the Aleutians and two will be on drifting ice islands in the Arctic. Others will be on shipboard or in cooperation with other countries, chiefly Canada and Denmark. Two U. S. IGY ionospheric vertical incidence sounding stations will be located at St. Johns, Newfoundland, and Thule, Greenland. Canada will maintain 33 stations and Denmark 11. Much of this effort will be devoted to the study of the aurora and the ionosphere. Cameras will be set up to photograph the entire sky periodically each night at the rate of about once a minute and reports on auroral conditions will be compiled about four times an hour. This activity may be substantially increased during brilliant displays and during the designated World Days. The work will also include cosmic-ray observations. Rocket flights will be made from the Fort Churchill base on Hudson Bay in connection with this effort.

In addition to the auroral observations in the polar regions, observations will be made all over the world and reports have been designated. Completion of the list of warning centers and national contacts for World Days has been announced.

The decision has been made to publish a journal *Annals of the International Geophysical Year* by CSAGI, the international office for the IGY. Plans are that this will be published by Pergamon Press.

In other parts of the world, away from polar regions, extensive plans are developing rapidly including, for example, a study of the deep water masses of the South Atlantic Ocean by the Woods Hole research vessel *Crawford*. Preliminary work is already in progress with the *Crawford* on an 1800-mile tour under the direction of F. C. Fuglister as chief scientist.

A new part of the study of Earth tides is to be undertaken on Hawaii by the establishment of a high-sensitivity gravimeter. This is to be done by the Institute of Geophysics of the University of California in cooperation with the University of Hawaii.

Work on the satellite program, on the general program in the Pacific and other oceanographic areas, as well as other phases of the IGY work are progressing pretty much according to plan so that on July 1 this great international endeavor, using the Earth as a whole as a laboratory, will get under way promptly.

STUDENT TRAINEE PROGRAMS OF THE GOVERNMENT—Announcement No. 74 of the Civil Service Commission, no closing date, indicates that a limited number of student trainees in the sciences, including oceanography and meteorology, will be appointed in grades GS-2 to GS-4 at salary rates of $2960 to $3415 per year,

these being essentially for summer work for students working toward their baccalaureate degrees. Upon completion of all requirements for a baccalaureate degree, including the appropriate specialized courses, the trainee will be promoted non-competitively to professional positions at the GS-5 Grade. Candidates should apply to the Civil Service Commission, Washington 25, D. C.

SESQUICENTENNIAL OF THE U. S. COAST AND GEODETIC SURVEY—The U. S. Coast and Geodetic Survey is now in the midst of its 150th anniversary celebration. This was started by a celebration dinner in Washington on February 5, and by the issue of a special commemorative postage stamp. Various scientific groups are observing this Sesquicentennial in various ways, and at our annual meeting the occasion will be appropriately observed at one of the general Union meetings. The American Congress on Surveying and Mapping, the Society of American Military Engineers, and the National Capital Section of the American Society of Civil Engineers are among those groups observing the celebration. On Monday, May 20, there will be a special observance by the Society of American Military Engineers which will include a crew of the Survey erecting a 100-foot portable tower and showing surveying techniques on the grounds of the Washington Monument, with an open house at the Washington headquarters. District offices in 13 cities will hold open house on staggered dates, and the public will be admitted to Survey ships that are in port.

SUMMER INSTITUTE FOR COLLEGE TEACHERS IN GEOLOGY—This will be held at the University of Illinois, June 17–August 10, 1957, with the aid of a grant from the National Science Foundation and under the directorship of D. M. Henderson, A. F. Hagner, and R. M. Garrels. Although applications closed April 1, inquiries should be addressed to the Department of Geology, University of Illinois, Urbana, Illinois.

OCEANOGRAPHIC EXPEDITION OF THE AGRICULTURAL AND MECHANICAL COLLEGE OF TEXAS—The Department of Oceanography and Meteorology of the A. and M. College of Texas conducted an expedition to the Bay of Campeche in the southwest part of the Gulf of Mexico during February and March, 1957, sponsored by the Office of Naval Research and aboard the research vessel *A. A. Jakkula*. The work included a study of marine geology and water mass characteristics of the area, with some emphasis on the chemical, biological, and meteorological studies.

NEW FELLOWSHIP AT COLORADO SCHOOL OF MINES—The Ohio Oil Company Foundation has established a fellowship at the Colorado School of Mines in the Department of Petroleum Engineering. The first fellowship of $3281 has been awarded to James J. Jennings of South Fork, Colorado. In addition to the fellowship fund, $1000 was presented to the School as an unrestricted grant.

NATIONAL ACADEMY PLAN TO AID HUNGARIAN REFUGEE SCIENTISTS—The National Academy of Sciences has established liaison with the authorities at Camp Kilmer, New Jersey, where refugees from Hungary have been arriving, to identify arrivals with advanced scholarly and professional training and to aid them in securing suitable employment in the United States. A relatively high percentage of the refugees are professional and technical workers. Any who have employment opportunities for such people should get in touch with the Office of Scientific Personnel of the National Academy of Sciences, 2101 Constitution Avenue, Washington 25, D. C.

NEW GRADUATE DEPARTMENT OF ASTRO-GEOPHYSICS ESTABLISHED AT THE UNIVERSITY OF COLORADO—Fundamental research in solar-terrestrial relations will be stressed in a graduate Department of Astro-Geophysics recently established at the University of Colorado. Facilities of the Department of Physics and High Altitude Observatory of the University and of the Radio Propagation Laboratory of the National Bureau of Standards will be available. The High Altitude Observatory is now offering two graduate fellowships with stipends of $1800 plus tuition to candidates for the Ph.D. degree.

ESTABLISHMENT OF DEEP-SEA OCEANOGRAPHIC STATIONS—During recent work in the Pacific, scientists of the Scripps Institution of Oceanography succeeded in establishing instrument stations in depths ranging from 3200 to 4700 meters, this in connection with an effort to obtain synoptic data over a large area. The moorings employed a taut wire with a primary float below the level of wave action. The stations were equipped with recorders, vertical instrument strings, a power supply, lights, and a target for radar. Sixteen were in use for a period of more than four months in the Northeast trade-wind area. The highest wind velocity noted during the period was about seven knots.

CLOUD-SEEDING EXPERIMENT IN CALIFORNIA—The Board of Supervisors of Santa Barbara County, Santa Barbara, California, is arranging to finance a randomized cloud-seeding experiment that will offer unparalleled opportunity for studying the effects of silver iodide smoke, produced by ground generators, on storms passing over mountainous areas. Several years ago, the Division of Water Resources of the California Department of Public Works investigated this with reference to commercial cloud-seeding operations using the assistance of the Statistical Laboratory of the University of California. No clear-cut answer was found. This randomized experiment, it is felt, will provide the answer. The Statistical Laboratory of the University of California and the North American Weather Consultants will undertake this experiment, which will be a cooperative enterprise with the actual seeding performed by North American Weather Consultants and with the California Department of Water Resources undertaking the responsibility for collecting rainfall data from a considerable number of raingages established on the target area and three other areas selected for comparison. The Weather Bureau and the Forest Service are helping in the matter of supplying equipment and in other ways, and the President's Advisory Committee on Weather Control will use the experiment for certain radar observations. Further details of the plan may be secured by writing to the Statistical Laboratory of the University of California in Berkeley or by consulting the January 11 issue of *Science*, pages 61–63.

NEW GEOPHYSICAL OBSERVATORY IN FRANCE—The French National Center for Scientific Research is building a new Geophysical Observatory near Pouilly-sur-Loire. Seven laboratory buildings and other service buildings to house special equipment are under construction, and houses are being built for 70 scientists and technologists who will form the permanent staff. The construction work alone will cost more than 600 million francs.

NEW PROSPECTING TECHNIQUE DEVELOPED AT CALIFORNIA INSTITUTE OF TECHNOLOGY—A new technique based on variations in the oxygen isotope ratio in surrounding rock has recently been outlined by the Division of Geological Sciences of the Institute, following a two-year field and laboratory examination of Leadville limestone in Colorado. As developed, the method is adaptable primarily to carbonate rock formations into which hot, ore-bearing fluids have been forced.

NEW TIDAL TOWER STATIONS UNDER STUDY—In northwestern France, on the River Rance, studies are now under way for the construction of a tidal power plant which will presumably be based on the 'bulb-unit' idea. The tentative idea is to build a 9000-kilowatt station, and present hopes are that the plant will start operating in 1960.

Studies are again under way in the Bay of Fundy between Maine and the Maritime Provinces of Canada to develop tidal power. Earlier plans on a portion of the Bay of Fundy were partially carried out during the 1930's, involving only a small arm of the Bay of Fundy and being entirely in the United States.

POSITIONS AVAILABLE ON U. S. IGY SATELLITE TRACKING PROGRAM—The Astrophysical Observatory of the Smithsonian Institution, 60 Garden Street, Cambridge 38, Massachusetts is accepting applications from scientists and technicians for positions in the Optical Satellite Tracking Program of the IGY. Interested persons should write to the Associate Director, Satellite Tracking Program, at the address mentioned above. Qualified personnel will be assigned as observers to IGY stations in the United States, and in foreign countries. Prior experience in physics, astronomy, or electronics is mandatory, and an academic degree in one of these fields is desirable.

TWO FELLOWSHIPS IN GEOPHYSICS AT SAINT LOUIS UNIVERSITY—The Department of Geophysics and Geophysical Engineering has announced the availability of two fellowships in support of graduate studies in geophysics, one of which is sponsored by the Gulf Research and Development Co. The stipend is $2000 per year plus the payment of tuition and fees. The second fellowship, likewise for graduate study, is provided by a grant from the Shell Oil Co. and carries a stipend of $1800 for the study of the fundamental nature and behavior of explosion-generated elastic waves. Inquiries should be addressed to the Dean of the Graduate School, Saint Louis University, 221 North Grand Boulevard, Saint Louis 3, Missouri.

GRANTS OF THE NATIONAL SCIENCE FOUNDATION—The National Science Foundation has recently announced 326 grants totalling almost six million dollars, a number of which are in support of various aspects of geophysics. Included in these are funds for an analysis by the Chesapeake Bay Institute of serial oceanographic observations; a study of the origin of meteorites at Massachusetts Institute of Technology; a gravity, seismic, and magnetic study in Utah and Eastern Nevada by the University of Utah, and a study of arid land limnology by the University of Washington.

COURSE IN AERIAL PHOTOGRAMMETRY—The Institut Géographique National of France is offering a theoretical and technical course in aerial photogrammetry, June 24–August 2, 1957. Inquiries should be addressed to Monsieur le Directeur de l'École Nationale des Sciences Géographiques, 2 Avenue Pasteur, Saint-Mandé (Seine). The number of attendants is limited to 25.

SYMPOSIUM ON IGY AT SAINT LOUIS UNIVERSITY—A Symposium sponsored by the Saint Louis Academy of Sciences was held on February 15, 1957, in Saint Louis, in commemoration of the death of our late President, James B. Macelwane. Taking part in the Symposium were Edward M. Brooks, Ross R. Heinrich, and Carl Kisslinger, with Victor J. Blum acting as moderator. At this Symposium an award was initiated entitled "Father James B. Macelwane, S. J., Awards in Meteorology."

NEW CURRICULUM IN MINERAL EXPLORATION AT MCGILL UNIVERSITY—McGill University has announced the offering of a new curriculum leading to a degree of Master of Science in Mineral Exploration. Candidates must have completed appropriate undergraduate courses or make up deficiencies for eligibility for the degree.

GROUND-WATER TREND IN OREGON—A recent release of the U. S. Geological Survey indicates that during 1956 the water levels in key observation wells throughout Oregon showed an average rise of 0.9 foot. Details may be secured from the U. S. Geological Survey Office in Portland, Oregon.

HIGH RATE OF WATER USE IN THE DELAWARE RIVER BASIN—Studies of the U. S. Geological Survey indicate that public and industrial water supplies are five times the national rate per square mile of area. Nearly six billion gallons per day were used during 1955, which is nearly a half million gallons per square mile per day. About 90 pct was taken from surface sources.

SERIES OF SYMPOSIA ON URANIUM HELD IN SOUTH AFRICA—A list of titles has recently been received relating to papers presented at Symposia on Uranium, sponsored by the Associated Scientific and Technical Societies of South Africa. These have recently been made available through the relaxation of security regulations governing the publication of papers relating to atomic energy. A list of the titles and other information may be secured by addressing the society group at P. O. Box 1183, Kelvin House, 75, Marshall St., Johannesburg, South Africa.

UNESCO SYMPOSIUM ON ARID-ZONE CLIMATOLOGY—The Eleventh Session of the Advisory Committee on

Arid Zone Research was held October 13–16, 1956, at Canberra, followed by this Symposium, October 17–20, 1956. After a four-day field trip, a continuation of the Session was held in Melbourne. About 70 scientists attended the Symposium, including 30 from overseas countries, with C. W. Thornthwaite serving as Chairman of the Symposium. Others attending from the United States were A. J. Drummond, Knut Schmidt-Nielsen, and F. A. Brooks. Questions concerning the proceedings should be sent to Mr. J. Swarbrick, Secretary, UNESCO Commission on Arid Lands, 19 Avenue Kléber, Paris 16, France.

CONFERENCE ON LIQUID SCINTILLATION COUNTING AT NORTHWESTERN UNIVERSITY—A Conference on Liquid Scintillation Counting will be held at the Technological Institute of Northwestern University, August 20–22, 1957. To be covered in the Conference are the following topics: coincidence counters, single channel counters, chemistry of liquid scintillators, and applications in biology and medicine, industry, archaeology, physics, chemistry, and engineering.

FORMATION OF UNION CARBIDE RESEARCH INSTITUTE—The Union Carbide and Carbon Corporation has announced the formation of this Institute on a site near Tarrytown, New York. The major purpose will be to study the physical and chemical behavior of matter under a great variety of conditions of pressure and temperature. It is expected that the facilities will be complete by the spring of 1958.

NEW VOLUME OF *Advances in Geophysics*—The third volume of *Advances in Geophysics* has now been published and, like the first two volumes, was edited by H. E. Landsberg and published by Academic Press. Further information will appear in the *Transactions* in due course.

NEW LABORATORY OF EARTH SCIENCES AT MIT—Massachusetts Institute of Technology has announced the establishment of a new Laboratory of Earth Sciences under the direction of Henry G. Houghton, Head of the Institute's Department of Meterology. The plan is that a new and integrated approach will be made to the experimental and theoretical investigations of man's environment: the atmosphere, the oceans, and the solid land masses including the interior of the Earth. It is intended that the Laboratory will become a research center for all those working in geology and the broad field of geophysics.

SURVEY OF STUDENTS IN GEOLOGY AND GEOPHYSICS—The American Geological Institute has recently completed a survey of students in geology and geophysics in colleges and universities of the United States in 1955–1956, and word concerning available scholarships, fellowships, and assistantships. This is Report No. 12. Copies may be secured at a price of 50 cents from the Institute at 2101 Constitution Avenue, Washington 25, D. C.

NEW ANTARCTIC INSTITUTE IN ARGENTINA—The Instituto Antartico Argentino has been established by the Argentine government at Cerrito 1248, Buenos Aires. The Institute is under the directorship of Rodolfo N. M. Panzarini, Rear Admiral of the Argentine Navy.

SPECIAL MEETING IN FLUID DYNAMICS—The Tenth Anniversary Meeting of the Division of Fluid Dynamics of the American Physical Society will be held at Lehigh University, November 25–27, 1957. More information may be secured from F. N. Frenkiel, Applied Physics Laboratory, The Johns Hopkins University, Silver Spring, Maryland.

Personalia

CHARLES C. BATES, formerly Deputy Director of the Division of Oceanography in the Hydrographic Office, has been appointed Environmental Systems Coordinator in the Office of the Development Coordinator of the Office of Naval Research.

JOHN S. BURLEW, Executive Vice President of Franklin Institute, was recently awarded an honorary degree of Doctor of Science by Drexel Institute of Technology.

FRANK L. CULLEY, Secretary of the Section of Geodesy, AGU, has left his duties with the U. S. Coast and Geodetic Survey and has taken up duties as Assistant Chief of the Geodetic Division of the Army Map Service.

JAMES L. DYSON, Chairman of the Department of Geology and Geography at Lafayette College, and former member of the Glacier Research Committee of the American Geophysical Union will deliver the Third Science Lecture of the 1957 Series at the Fairchild Tropical Garden, Coconut Grove, Florida, on March 15th. His subject will be "Glaciers and the landscapes they make."

RICHARD FOSTER FLINT, Professor of Geology at Yale University, has been given a travel grant by the Wenner-Gren Foundation for work in Africa to examine sites where evidence of ancient man has been found. His itinerary will include the Belgian Congo, Uganda, Kenya, Tanganyika, Rhodesia, and the Union of South Africa.

R. P. GOLDTHWAIT, Professor of Geology at Ohio State University, has taken up duties for a year with the Geological Survey of New Zealand at Christchurch.

ROSS GUNN, Director of the Division of Physical Science of the U. S. Weather Bureau, has been awarded the gold medal of the Department of Commerce for outstanding contributions to public service, the Nation, and humanity.

BENO GUTENBERG, Director of the Seismological Laboratory of the California Institute of Technology, and Fifteenth Recipient of the William Bowie Medal in 1953, has been given the Emil Wiechert Medal of the German Geophysical Association in appreciation of his accomplishments in seismology and in the investigation

of the structure of the Earth. This is the second award of the medal which was founded in 1955.

FLOYD HOUGH, Chief of the Geodetic Division of the Army Map Service, retired January 31, 1957. David L. Mills has been designated as his successor.

JOSEPH KAPLAN, Professor of Physics at the University of California and Chairman of the U. S. National Committee for the IGY, was recently given the annual Award of Merit by the Phi Delta Epsilon Fraternity for his contributions to science.

LESTER MACHTA has been awarded the Gold Medal of the Department of Commerce for outstanding contributions to public service, the Nation, and humanity.

CONRAD P. MOOK, Editor in Meteorology for the *Transactions* of AGU, has left his work with the U. S. Weather Bureau and joined the staff of the Diamond Ordnance Fuze Laboratories in Washington.

THORNDIKE SAVILLE, Dean of the College of Engineering of New York University, will retire in September, 1957. He became associated with New York University in 1932 and became Dean in 1935.

HERBERT C. S. THOM, who has been serving as Chief Climatologist of the President's Advisory Committee on Weather Control for the last two years, has now returned to his position in the Office of Climatology of the Weather Bureau.

R. G. VERYARD of the United Kingdom was elected President of the Commission of Climatology of the World Meteorological Organization during the meeting recently held in Washington. C. C. Boughner of Canada was elected Vice President.

R. A. WORK, Head of the Snow Surveys and Water Supply Forecasting Section of the Soil Conservation Service in Portland, Oregon, has recently returned from a six weeks' tour of duty in Iraq where he assisted the Hydrologic Survey in the establishment of a snow-course network and the training of personnel in water-supply forecasting procedures.

IRVIN H. ALTHOUSE, of the firm Althouse-Strauss Engineering Services of Porterville, California, died January 8, at the age of 69. He was born at Fremont, Nebraska. His professional career was devoted entirely to the practice of civil engineering, beginning in the Porterville area in 1908, devoting his energies chiefly to problems of irrigation, the development of water wells, and related projects. He had been a member of AGU since 1941.

GEORGE BENEDICT LAMB, Division Exploration Manager of the Gulf Oil Corporation, died in Houston, Texas, September 20, 1956, at the age of 60. He was born in Washington, D. C. and took his baccalaureate degree from the University of Pittsburgh in physics and mathematics and a second one from Massachusetts Institute of Technology in electrical and mechanical engineering. In 1929, he entered the service of the Gulf Research and Development Company in Pittsburgh as a geophysics instrument designer. In 1939, he transferred to the Gulf Oil Company in Houston, Texas, where he engaged in geophysical exploration work up to the time of his death. He had been a member of AGU since 1939.

GEORGE DAVIS LOUDERBACK, Professor Emeritus of Geology at the University of California at Berkeley, died January 27, at the age of 82. He was born in San Francisco. He took his baccalaureate degree from the University of California in 1896, and his Ph.D. in 1899. He was awarded an LL.D. in 1946. In 1900, he became a Professor of Geology and Physics at the University of Nevada, where he continued until 1906. From 1906 until 1944 he had served continuously at his alma mater and served as Dean of the College of Letters and Sciences from 1920 to 1922 and 1930 to 1939. In addition to his work at the University, he was frequently called on for other assignments and was in charge of a geological expedition to China organized by the Standard Oil Co. in 1914–1915, serving the Chinese government from 1915–1916. His work also included assignments by the U. S. Bureau of Mines, the U. S. Geological Survey, and other groups. He had been a member of AGU since 1934.

Suggestions to Authors on Preparation of Manuscripts for the Transactions, American Geophysical Union

General—The American Geophysical Union welcomes contributions on basic geophysical topics, written in English and consonant with the objectives of its *Transactions*. Contributors may be members or nonmembers. The Union assumes no responsibility for their statements and conclusions. The Editorial and Publication Committee decides on approval or rejection of each manuscript, directs any needed editing or condensation, and determines in which of the several departments of the *Transactions* the approved material shall appear.

The Committee takes a liberal attitude toward papers involving controversial points and those advancing novel and unorthodox ideas, but it is essential that the reasoning be objective and sound, that the supporting data be pertinent, and that the points at issue be defined. Papers dealing mainly with engineering, climatological, and similar applications will not be approved; neither will those that involve no new principle, those that are just a reworking of material already published, or those that advocate personal interests. Papers that use specific observations to test newly emergent concepts are viewed favorably, but chronicles of data relating to commonplace events or individual localities are not.

Acceptance of papers for presentation at meetings of the Union or of its Sections or Regional Branches does not imply acceptance for publication, but such papers are, of course, welcomed for consideration for publication in the *Transactions*. It is against the policy of the Union to publish papers simultaneously with, or subsequent to, publication elsewhere. In view of the heavy burden carried by members of the Committee, and by referees, a paper once submitted should be regarded as unavailable for withdrawal or for alternative publication elsewhere unless released by the AGU.

It is the author's duty to acquaint himself with the pertinent work done by others, so that the originality of his work will not be in question; and to prepare his material in logical and attractive form, so that it may be read by a specialist in his field without need of interpolating the author's intentions. To this end, and to facilitate editing and preparation for publication, authors are requested to comply fully with these suggestions. *Manuscripts grossly at variance with these suggestions will be returned for revision.*

If the author has difficulty in expressing his thoughts in English, he should submit both an original version in his accustomed language and a competent English translation.

Approved contributions will be generally scheduled in order of receipt, subject to maintaining a reasonable balance in each issue among the fields of geophysics as represented by the Sections of the AGU.

Aids in preparation of manuscript—In general, the editors will adopt the conventions of the Chicago Style Manual [*University of Chicago Press*, 1949]. In editing, every effort will be made to preserve the author's style, bearing in mind the fact that certain conventions are essential in any serial journal. Recommended aids to clear writing are: *Emberger* and *Hall* [1955], *Trelease* [1951], and *Wood* and *Lane* [1945]. The pitfalls of expression that trap the unseasoned author are highlighted in student handbooks [*Bell*, 1939; *Howell*, 1940].

Text—The author is urged to allow adequate time before adopting the final draft, both for a fresh and deliberate appraisal looking toward condensation or reorganization, and for a review by a disinterested colleague to assist in achieving high standards of clarity, logical integrity, syntactical smoothness, and, above all, conciseness. Hold to a minimum treatments of previous work, descriptions of apparatus and methods, and passages that tell how tables are computed or how graphs are constructed. Present data once only, in text, tables, or graphs, except where repetition serves a distinct purpose. The right is reserved to limit the space assigned to any contribution.

Examine recent issues of the *Transactions* for style and format, especially with regard to preparation of illustrations. For the final manuscript use 16-pound (or heavier) letter-size typing paper. Type triple- or double-space, with wide margins, on one side only. Proofread finished manuscript carefully before submission, looking especially for ungrammatical passages, incongruities, misspelled words, and errors in referencing and in numbering. Transmit three copies to the office of the AGU, complete with illustrations.

Limit reports of scientific and research committees to about 3000 words. If more material is on hand, consider presentation of some of it as one or more scientific papers. Do not submit routine or

'no progress' reports. Reports of negative results, however, may be important.

Closing dates for discussions are announced at the end of each paper and report, and an author will be given a reasonable time for preparation of a closure. Make discussions brief, preferably less than one-fourth the length of the original paper. A discussion should be an objective analysis and not a supplementary treatment or addendum. However, data supporting or controverting the paper are welcome.

Abstracts—Provide a brief, informative abstract at the beginning of the paper. The abstract should be a concise but comprehensive summary of the significant contributions to knowledge contained in a paper, suitable for separate publication and adequate for the preparation of general indexes to geophysical literature. It should bring out not only the major contributions but also any important incidental contents to which the title gives no clue. Many geophysicists will not have time to read the paper in full. The abstract should indicate, as pertinent, the method of attack (empirical, statistical, observational, theoretical, etc.), the basic principles involved, the type of data used, their range or scope, and the degree of accuracy attained. References, figures, and tables should not be cited in the abstract, since they would not be intelligible when separated from the paper. Any special features of the paper, such as an extensive bibliography, should be mentioned.

An abstract is not a table of contents or an introduction. The opening sentence should be framed so as to avoid repetition of the title, but if the title is not sufficiently indicative of the subject, the opening sentence should fill this gap. The abstract should usually indicate the objectives of the investigation. Use such qualifying adjectives as brief, extensive, theoretical, etc., drawing attention to new facts, such as new relationships, physical constants, or numerical data.

Title and headings—Make the title short, preferably less than 70 letters and spaces. Choose subheadings carefully to clarify and accent the logical arrangement of the paper. They should normally be arranged like those in this article; headings of more than one rank should not be used unless imperatively needed.

Tables—Make reference in the text to all tables by number, in sequence mentioned. Provide each table with a concise, descriptive title. Make certain that column headings are short and self-explanatory, using footnotes for more complete explanation where necessary. Indicate unit at head of each column, beneath the box-head. Avoid repetition of columns and entries.

Units and nomenclature—Use the 24-hour system of time notation, as for example 17h 22m, indicating the reference base by GMT, UT, EST, or other commonly used notation. Use standard rather than proprietary terms. Give preference to the metric system in those geophysical fields in which it is appropriate. Use names of units that are compounded from the fundamental ones according to scientific usage. Omit periods after abbreviations of units and after chemical and mathematical symbols.

Great care is required to insure accuracy and legibility of all formulas, with special attention to exponents and subscripts. So far as usage permits, avoid Greek letters, unusual symbols and cumbersome notations. A script ℓ is used as a symbol rather than the typed letter, to avoid confusion with the numeral 1. Mark handwritten letters *C*, *O*, *P*, *S*, *V*, *W*, and the like 'cap' or 'lc' to show whether they are intended as capitals or lower-case. Letter symbols that stand for physical quantities may require special marking—single underscoring for italics, a wavy single underscoring for bold face (vectors). Bold face must be marked in *every* instance; italics, though used systematically, need be marked only if the expression containing the symbols occurs in running text, or if it also contains nonitalicized letters, such as abbreviated functional symbols (ln, cos, exp), unit abbreviations, or chemical symbols. For guidance in preparing mathematical material, refer to *American Mathematical Society* [1943].

References and footnotes—Indicate references in the text by inserting in square brackets the author's surname, a comma, and the year of publication, the name being underscored, thus: [Krumbein, 1955]. If the name is part of the text, only the year is bracketed. If there are two or more references citing different papers published in the same year by the same author, distinguish them by the letters a, b, c, after the year. At the end of the paper, list all references alphabetically by authors' names. Include in each entry the following: Surname of senior author, followed by his initials; surnames of junior authors, each *preceded* by his initials; title of paper (or book); publication or journal; number of volume; inclusive pages; year of publication. Abbreviations for journals follow, in general, the style adopted in *Physics Abstracts*. If in doubt, give the full title of the publication or journal. Where a book is cited, insert the publisher's name, the city of publication, and the number of pages. Give credit for or acknowledge

unpublished reports and private communications in the text and not as references. Avoid footnotes to the text; replace by parenthetic sentences wherever possible.

Acknowledgments—Make these in a brief closing paragraph, holding them to a minimum.

Illustrations—So far as possible, illustrations should be planned for reduction to the column width of $2\frac{3}{8}$ inches or 68 mm; but some may be larger, in accordance with their character and relative importance. A full-page illustration would ordinarily be slightly smaller in one direction than the full 14 by 21 cm ($5\frac{1}{2}$ by $8\frac{1}{4}$ inch) page size, to allow for a caption. Original drawings should be about twice the final (printed) dimensions, and no illustration should be submitted in a form so small as to require enlarging. Supply originals or glossy photographic prints for reproduction, and ozalid or other clear prints for the second and third manuscript copies.

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Make drawings and maps with black india ink on white paper or tracing cloth. Omit all nonessential detail, especially hairlines and closely spaced grids of graph paper. Show only those plotted points that represent observations forming the basis for curves. Use graphic scales, not numerical ones. On maps, show north direction and all geographic features mentioned in the text, but omit all nonessential features. Blue-line drawings, blue prints, colored drawings and photographs, and graphs drawn on coordinate paper of any color other than blue, will not be accepted unless the author pays for redrafting.

When illustration of an instrument or piece of equipment is needed, a drawing that brings out the essentials clearly is preferable to a photograph. Photographs should be submitted as unmounted, glossy prints, of suitable quality for engraving, with good intensity and contrast. Low-contrast detail, particularly in highlight and shadow areas, is lost in printing. Cropping and enlargement are often desirable to bring out pertinent elements. Supply negatives if suitable enlargements cannot be furnished. Identify prints by putting figure numbers very lightly on backs, with HB or softer pencil. Avoid using paper clips on photographs.

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Proofreading and reprints—Galley proofs will be sent to the author for proofreading. Place orders for reprints when returning this proof copy. The schedule of prices will accompany the proof.

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REFERENCES

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Special Announcements

ELEVENTH GENERAL ASSEMBLY OF IUGG IN TORONTO, ONTARIO, CANADA—Plans for this meeting are now entering the final stages. All seven associations will have extensive programs. Those from the United States who desire to attend should get in touch with the office of AGU without further delay. As noted in an advertisement in this issue of the *Transactions*, the Canadian Organizing Committee has reserved accommodations for a sizable number in the dormitories of the University of Toronto. Elaborate plans are being developed not only with reference to technical and scientific meetings but with regard to the social aspects of this meeting as well.

PLANS OF THE NORTH CENTRAL REGIONAL GROUP—Tentative plans are developing for a meeting in the Midwest possibly in Saint Louis or perhaps in Indianapolis in late December, 1957, in connection with the meeting of the American Association for the Advancement of Science. Meeting plans are in the hands of Edward M. Brooks, Chairman (Saint Louis University, Saint Louis, Missouri) and Russell G. Mann, Secretary-Treasurer (U. S. Weather Bureau River Forecast Center, Saint Louis, Missouri). Should the meeting be in Indianapolis, it will have the active cooperation of William C. Krumbein, one of AGU's members on the Council of the AAAS (Northwestern University, Evanston, Illinois). Watch these announcements for further word.

PACIFIC NORTHWEST REGIONAL MEETING TO BE HELD IN NOVEMBER—Tentative plans have been laid to hold the meeting in November, 1957, in Portland, Oregon. Norbert Leupold (P. O. Box 5082, Portland 13, Oregon) has been designated the new Chairman, beginning July 1, 1957, succeeding Clifford A. Barnes (University of Washington, Seattle 5, Washington). The Secretary of the Regional Committee is Franklin I. Badgley (Department of Meteorology, University of Washington, Seattle 5, Washington). Inquiries and ideas should be forwarded to one of these three. Watch these announcements for further word.

MEETING OF THE PACIFIC SOUTHWEST REGION—Tentative plans are being developed relative to the meeting to be held in the Pacific Southwest Region in January or February, 1958. Interested persons should get in touch with Vito A. Vanoni, Chairman of the Regional Committee (California Institute of Technology, Pasadena 4, California), or R. Corday Counts, Jr., Secretary (1472 Cortez Avenue, Burlingame, California). Watch these announcements for further word.

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Nineteenth Award of the William Bowie Medal

Citation

Prepared and presented by BENO GUTENBERG

Mr. Chairman, Members and Friends of the American Geophysical Union: I am happy to present an old friend, Maurice Ewing, as recipient of the Bowie Medal.

The William Bowie Medal was established by vote of the Executive Committee of the American Geophysical Union on March 1, 1939 (Trans. Amer. Geophys. Union, 1939, p. 456). "It is to be awarded for distinguished attainment and outstanding contribution to the advancement of cooperative research in fundamental geophysics." The award "is to be made annually or less frequently upon authorization by the Executive Committee of the Union." The medal bears the inscription "unselfish cooperation in research."

Nearly every year attempts have been made to formulate in more detail requirements for the award. Under the guidance of Dr. Bucher, the present committee has agreed on the following principles:

(1) The recipient must be outstanding for his contributions to fundamental geophysics and must be considered as worthy of distinction in this country and abroad.

(2) The expression "cooperative research" we interpret to mean that the recipient has extended his activities beyond the limits of his own specialty to active work with scientists in other fields having acquainted himself with the pertinent literature, and that he has contributed, unafraid of critical

William Maurice Ewing
Recipient, Nineteenth Award
William Bowie Medal, April 30, 1957

review, to research in diverse geophysical fields by correspondence and publications.

(3) The word "unselfish" we interpret to mean willingness on the recipient's part to step out of his recognized field of competence to work with men in other sciences where he is more or less dependent on the knowledge of others and sacrifices time and energy in meetings and correspondence with them, even if these cannot be expected to bring tangible rewards in the form of papers by his own pen. As a matter of course, the recipient's research and publications should be free from personal propaganda.

It was also the opinion of the Committee members that within reasonable time intervals candidates for the award should be chosen from all sections of the Union. However, the classification into sections should not be looked upon mechanically. It does not any longer have the scientific importance which it had at the time when sections were formed. To an increasing degree, research in various fields is necessary to investigate a single problem. Examples include combination of studies of paleomagnetism and changes in climates; of gravity anomalies, tectonic processes, volcanic activity and earthquakes; of meteorological and oceanographic research; of auroras, conditions in the ionosphere and terrestrial magnetism. Many other examples are provided by our medalist. He has participated in the investigations of the coupling of sound waves in the atmosphere and of elastic waves in the ground; of the generation of tidal waves by the atmospheric waves produced in the Krakatoa explosion and of waves in lakes by rapid changes in air pressure. His main achievement, his successful introduction of geophysical tools into deep sea exploration, combines research involving fields of several sections.

The expression "fundamental geophysics" has been considered by some to exclude applied geophysics. However, in many instances applied geophysicists have contributed appreciably to fundamental research in general geophysics.

Originally, every geophysicist had to be familiar with all major fundamental problems of physics of the solid Earth, the ocean, and the atmosphere. The rapid growth of the science resulted in specialization and in separation into sections. We are now returning to a unified science of geophysics; symposia, combining several sections, are increasing in numbers and extent. The importance of the sections is shifting more and more to their administrative purposes.

On the basis of the requirements as interpreted by the Committee, its members have unanimously and, I may say, enthusiastically agreed on the choice of the medalist. Maurice Ewing's standing in this country and abroad is attested to by the high honors he has received, such as the Arthur Day Medal of the Geological Society of America, and the Honorary Doctor's Degree which the University of Utrecht has recently bestowed upon him. The breadth of his cooperation is indicated by the name of the institution which he heads, the "Lamont *Geological* Observatory." When he chose as the central object of his life's work the physical nature of the ocean's floor, the largest *terra incognita* on the face of the Earth, he knew that he would have to work hand in hand with geologists. Many geologists on both sides of the ocean have worked with Ewing and his men. His active coworkers include students of sedimentation, micropaleontologists, and even marine zoologists. He has liberally given information and advice to fellow scientists in correspondence and in discussions. Repeatedly I have received results from him long before their publication. I do not know of any candidate who has a greater amount of cooperative research in fundamental geophysics to his credit than our medalist.

It is with great pleasure, Mr. Chairman, that I present to you, Maurice Ewing.

Presentation

LEASON H. ADAMS

Maurice Ewing, on behalf of the American Geophysical Union I have much pleasure in presenting to you the William Bowie Medal for Unselfish Cooperation in Research. My sincere congratulations!

Response and Acceptance

MAURICE EWING

This award is accepted in deep humility, and with the thought that much of my work has been done with various members of the staff of the Lamont Geological Observatory.

William Bowie played a leading part in directing my studies toward problems of the ocean basins and in helping to provide the necessary facilities. He and Richard Field, whose insight and efforts were largely responsible for establishment of the Award, paid an unannounced visit to my office in Lehigh University in November 1934. They came as spokesmen of a small committee, of which they and Walter Bucher were leading members. Their mission was to stimulate and encourage me to undertake the application of various techniques of geophysical prospecting to investigation of the ocean basins. They aroused an interest which has dominated my life from that day to this.

All three members of the Bowie Medal Committee have lent encouragement and assistance to our research program. Upon initiating studies in earthquake seismology, we naturally turned to the Seismological Laboratory in Pasadena as a model and repeatedly received generous advice from Beno Gutenberg.

From the Geophysical Laboratory, we have copied or borrowed many features of organization and operation. Even the cards on which our publications are announced are like theirs. While Director of that renowned institution, Leason Adams encouraged us to emphasize the study of deep-sea sediment cores and arranged for the gift of the winch which is now in use on the research vessel *Vema*.

Walter Bucher, our esteemed colleague and patient counsellor, has followed the program closely from the start, and has helped in surmounting many obstacles. Time after time, he has guided us to understanding of the significance of measurements made and has pointed the direction to the next likely target.

For a number of years before the second World War, William Bowie paid a brief annual visit to Lehigh University. He gave lectures to the geologists and the civil engineers and also held informal conferences. For many of us this visit was truly the climax of the year. We learned from him in all matters, great and small. The first time I saw William Bowie he was the presiding officer of a meeting of the American Geophysical Union in the room in which we are now assembled. Many of those present will remember the dignity with which he conducted a meeting and his warm and encouraging manner toward the speakers—particularly the younger ones.

Every member of the American Geophysical Union may well take pride in the Medal which has now been awarded nineteen times. It affords a signal honor to each recipient, and it also serves to keep alive the inspiring memory of William Bowie.

Gravity Observations at Sea in USS *Corsair**

J. Lamar Worzel and G. Lynn Shurbet

Abstract—In 1952, gravity observations at sea were made in USS *Corsair* (SS 435) with the Vening Meinesz pendulum apparatus at 31 positions from New London, Connecticut, to Nassau, Bahama Islands. The principal facts for these observations, including free-air and simple Bouguer anomalies, are presented in this paper. Isostatic corrections are being computed by the Mapping and Charting Research Laboratory, Ohio State University, under the direction of W. A. Heiskanen.

Introduction—One purpose of the gravity program carried on at the Lamont Geological Observatory is to contribute to a world-wide network of gravity stations for studies of the figure of the Earth. The 31 gravity observations at sea (Fig. 1) reported in this paper result from one submarine cruise undertaken by the authors as a part of this program [*Worzel, Shurbet,* and *Ewing,* 1955b].

Instrumentation—The gravity observations were made with a pendulum apparatus developed by *Vening Meinesz* [1929], with modifications to improve techniques of observation and data reduction [*Worzel* and *Ewing,* 1950, 1952; *Worzel, Shurbet,* and *Ewing,* 1955a, b]. Horizontal accelerations were observed with a long-period pendulum apparatus designed by *Vening Meinesz* [1941].

Observations—Only minor modifications have been made in the observation program of *Vening Meinesz* [1929]. A single speed was used for the recording paper, horizontal accelerations were observed with a long-period pendulum apparatus, and a crystal chronometer, operating a synchronous motor to break the light beam to the pendulums, replaced the spring chronometers.

Computations—Pendulum periods read from the records were corrected for temperature, air density, isochronism, chronometer rate, tilt of the swinging plane, and amplitude. Gravity values at the depth of submergence were corrected for the second order effects of acceleration [*Browne,* 1937], depth of submergence, and the Eötvös effect, yielding values of observed gravity at the sea surface. Each value is the average value of observed gravity over a horizontal distance of about one mile, since each observation requires about 30 minutes while the submarine is traveling at about two knots. The International Formula of Gravity of 1930 was used to compute the free-air anomalies. *Ewing, Worzel,* and *Shurbet* (in press) have estimated the uncertainty of free-air anomalies determined by typical observations such as those made during this cruise to be ± 3.6 mgal.

Temperature and density coefficients—The coefficients listed below for pendulums 4, 5, and 6, are discussed by *Ewing, Worzel,* and *Shurbet* [in press]. These coefficients are adopted for the *Corsair* cruise: Temperature coefficients (determined in 1947), $C_4 = 98.4 \times 10^{-7}$ sec/°C, $C_5 = 99.0 \times 10^{-7}$ sec/°C, $C_6 = 98.0 \times 10^{-7}$ sec/°C. Density coefficients (determined in 1948), $D_4 = 1319 \times 10^{-7}$ sec/unit relative air density, $D_5 = 1346 \times 10^{-7}$ sec/unit relative air density, $D_6 = 1337 \times 10^{-7}$ sec/unit relative air density.

Primary base observations—The Lamont Geological Observatory (LGO) Base no. 1 (serial 1501) is the primary base for these observations. Determinations of the LGO Base value (980.2584 cm/sec²) from the U. S. Coast and Geodetic Survey base (980.118 cm/sec²) in the Department of Commerce Building, Washington, D. C., have been presented by *Shurbet* and *Worzel* [in press]. Our Columbia University Base (980.268 cm/sec²) served as an intermediate base in these determinations.

Records at the LGO Base for pendulum standardization for the *Corsair* cruise are those made in November 1951, before a cruise of USS *Toro* beginning in December 1951. There was no opportunity to return the apparatus to the LGO Base until after the *Corsair* cruise. Because of a misunderstanding, observations were not made at the LGO Base after the *Corsair* cruise until mass was added to Pendulum 5 to correct for a change in period brought about by too large accelerations during one observation of the *Toro* cruise. All three of the pendulums were handled considerably while the period was being adjusted, so we have not compared base observations after this work with those before the *Toro* cruise. The periods determined at the LGO Base before the *Toro* cruise are shown in Table 1.

* Contribution number 237, Lamont Geological Observatory, Columbia University.

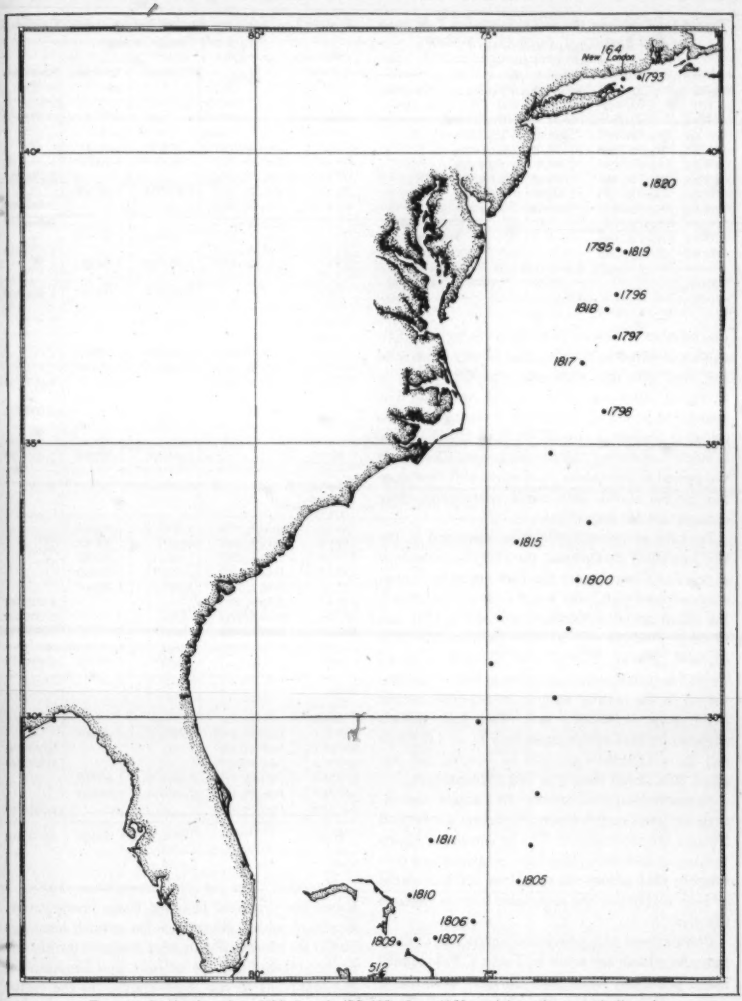

FIG. 1 – Station locations USS *Corsair* (SS 435), June 1952; serial numbers are indicated

In Table 2 periods determined at New London at the beginning and end of both the *Toro* and *Corsair* cruises are shown. Inspection of the mean periods for each group of observations shows that the mean period of Pendulum 4 decreased by 21×10^{-7} sec (about four mgal) during this interval. This change in period is more than usually experienced, but it is not too serious considering

TABLE 1 – *Pendulum standardization before Toro cruise at LGO Base No. 1, 41–00.3N., 73–54.5W, g = 980.2584 cm/sec²*

Observation	Date	Pendulum 4	Pendulum 5	Pendulum 6
VO 2-1	Nov. 14, 1951	1.0055973	1.0055698	...
VO 2-2	Nov. 15, 1951	1.0055982	1.0055696	...
VO 2-3	Nov. 15, 1951	1.0055978	1.0055695	...
VO 2-4	Nov. 16, 1951	1.0055977	1.0055693	...
VO 2-5	Nov. 16, 1951	1.0055978	1.0055693	...
VO 2-6	Nov. 16, 1951	1.0055987	1.0055697	...
VO 2-7	Nov. 16, 1951	...	...	1.0055978
VO 2-8	Nov. 16, 1951	...	...	1.0055974
VO 2-9	Nov. 16, 1951	...	...	1.0055989
Mean		1.0055979	1.0055695	1.0055980

the number of observations intervening, the difficulties involved in making port observations, and the fact that the apparatus was dismantled in changing submarines during the interval. The change in period of Pendulum 5 during the *Toro* cruise is obvious; however, no appreciable change is evidenced during the *Corsair* cruise. Changes in the period of Pendulum 6 are noticeable, but since this period affects only minor corrections, these changes are not important.

In view of the circumstances discussed in the two preceding paragraphs, the periods determined at the LGO Base before the *Toro* cruise have been adopted for Pendulums 4 and 6. For Pendulum 5 the mean period determined by records CO1 and CO31 (1.0055430 sec) at New London (980.2954 cm/sec², [*Ewing, Worzel,* and *Shurbet,* in press] Table 14, with free-air correction applied) was converted in the normal manner to a period for the LGO Base (1.0055619 sec). The base periods adopted for the *Corsair* cruise are: T_4 = 1.0055979 sec, T_5 = 1.0055619 sec, and T_6 = 1.0055980 sec, all at 30°C, LGO Base g = 980.2584 cm/sec².

Secondary base observations—In Table 3 observations at New London (using Pendulum 4 only) and Nassau are summarized. The agreement of observations at each secondary base is satisfactory considering that serious accelerations are introduced at port stations as the submarine bounced against the pier.

Comparisons with previous observations at these secondary bases are made in Table 4. Values published previously have been changed when necessary to base them on the Commerce Building Base (980.118 cm/sec²). The agreement between all values in Table 4 is satisfactory considering the difficulties involved in port observations with the pendulum apparatus.

TABLE 2 – *Pendulum standardization at New London, Toro and Corsair cruises*

Observation	Date	Pendulum 4	Pendulum 5	Pendulum 6
Before *Toro* cruise				
TO 1-1	Dec. 29, 1951	1.0055799	1.0055522	...
TO 1-2	Dec. 30, 1951	1.0055788	1.0055518	...
TO 1-3	Dec. 30, 1951	....	....	1.0055811
TO 1-4	Dec. 31, 1951	1.0055788	1.0055499	...
TO 1-5	Dec. 31, 1951	....	....	1.0055800
TO 1-6	Dec. 31, 1951	....	....	1.0055787
TO 1-7	Dec. 31, 1951	1.0055812	1.0055532	...
TO 1-8	Dec. 31, 1951	....	....	1.0055814
TO 1-9	Dec. 31, 1951	1.0055781	1.0055505	...
Mean		1.0055794	1.0055515	1.0055803
After *Toro* cruise				
TO 125-1	May 16, 1952	1.0055784	1.0055405	...
TO 125-2	May 17, 1952	1.0055778	1.0055407	...
TO 125-3	May 17, 1952	....	....	1.0055796
TO 125-4	May 17, 1952	1.0055775	1.0055415	...
TO 125-5	May 17, 1952	....	....	1.0055790
TO 125-6	May 17, 1952	1.0055767	1.0055405	...
Mean		1.0055776	1.0055408	1.0055793
Before *Corsair* cruise				
CO 1-2	June 1, 1952	1.0055773	1.0055437	...
CO 1-3	June 1, 1952	1.0055777	1.0055418	...
CO 1-4	June 1, 1952	1.0055769	1.0055427	...
CO 1-5	June 1, 1952	1.0055775	1.0055442	...
CO 1-6	June 1, 1952	1.0055779	1.0055437	...
CO 1-7	June 1, 1952	....	....	1.0055761
CO 1-8	June 1, 1952	....	....	1.0055752
CO 1-9	June 1, 1952	....	....	1.0055761
Mean		1.0055775	1.0055432	1.0055758
After *Corsair* cruise				
CO 31-1	June 13, 1952	1.0055780	1.0055433	...
CO 31-2	June 14, 1952	....	....	1.0055768
CO 31-3	June 14, 1952	....	....	1.0055768
CO 31-4	June 14, 1952	1.0055770	1.0055426	...
CO 31-5	June 14, 1952	1.0055768	1.0055418	...
CO 31-6	June 14, 1952	....	....	1.0055768
Mean		1.0055773	1.0055426	1.0055768

Principal facts for the observations—Table 5 shows the principal facts for these observations. Pertinent added information on column headings is: (2) the observation number assigned during the cruise; (4) and (5) the latitude and longitude of the mid-point of the observations; (6) the water depth in meters corrected according to the tables of *Matthews* [1939]; (8) the value of theoretical gravity in cm/sec² by the International Formula of Gravity of 1930, $\gamma_0 = 978.0490\ (1 + 0.0052884 \sin^2 \phi - 0.0000059 \sin^2 2\phi)$, and (10) the simple

TABLE 3 – *Gravity observations at secondary bases, Corsair cruise*

Observation	Date	Pendulum 4	Pendulum 5	Pendulums 4 & 5
New London, Conn., 41-23.6N, 72-05.6W				
CO 1-2	May 31, 1952	980.2981	...	...
CO 1-3	June 1, 1952	980.2973	...	...
CO 1-4	June 1, 1952	980.2988	...	...
CO 1-5	June 1, 1952	980.2977	...	...
CO 1-6	June 1, 1952	980.2969		
Serial No. 164 (c) Adopted value 980.298				
Nassau, Bahama Islands, 25-05.2N, 77-20.1W				
CO 19-1	June 8, 1952	979.0315	979.0272	979.0294
CO 19-3	June 8, 1952	979.0300	979.0272	979.0286
CO 19-4	June 8, 1952	979.0292	979.0285	979.0289
CO 19-6	June 8, 1952	979.0313	979.0293	979.0303
Serial No. 512 (a) Adopted value				979.029
New London, Conn., 41-23.6N, 72-05.6W				
CO 31-1	June 13, 1952	980.2967	...	...
CO 31-4	June 14, 1952	980.2986	...	...
CO 31-5	June 14, 1952	980.2990	...	...
Serial No. 164 (c) Adopted value 980.298				

TABLE 4 – *Comparison of gravity values at secondary bases, Corsair cruise*

Observation	Date	Latitude	Longitude	Elev.	Gravity
New London, Connecticut					
Corsair	1952	41-23.6N	72-05.6W	0	980.298
Corsair	1952	41-23.6N	72-05.6W	0	980.298
Conger, cruise III[d]	1954	41-23.5N	72-05.5W	0	980.294
Conger, cruise III[d]	1954	41-23.6N	72-05.6W	0	980.294
Conger, cruise III[d]	1954	41-23.5N	72-05.5W	0	980.295
Diablo[a]	1953	41-23.6N	72-05.6W	0	980.296
Diablo[a]	1953	41-23.5N	72-05.5W	0	980.297
Argonaut[b]	1948	41-23.6N	72-05.5W	0	980.295
Argonaut[b]	1948	41-23.5N	72-05.5W	0	980.298
Tusk[b]	1947	41-23.6N	72-05.5W	0	980.294
Frost gravimeter[b]	1948	41-23.6N	72-05.5W	0	980.2948
Frost gravimeter[b]	1948	41-23.5N	72-05.5W	0	980.2940
Nassau, Bahama Islands					
Corsair	1952	25-05.2N	77-20.1W	0	979.029
Argonaut[b]	1948	25-05.2N	77-20.2W	0	979.032
Madregal[b]	1948	25-05.2N	77-20.2W	0	979.031
S-48[e]	1932	...	...	0	979.030
USC & GS[e]	1930	25-05.2N	77-21.0W	4	979.028

[a] *Shubert* and *Worzel* [in press].
[b] *Ewing, Worzel,* and *Shurbet* [1956].
[c] *Collins* [1933].
[d] *Shurbet* and *Worzel* [1957].
[e] Principal facts for gravity stations in the **Bahamas** and the West Indies, G-50, Part I.

TABLE 5 – *Gravity observations at sea U.S.S. Corsair* (SS 435); *observers, J. Lamar Worzel and G. Lynn Shurbet; based on LGO Base (980.2584 cm/sec²)*

Serial no. (1)	Station no. (2)	Date (3)	Latitude north (4)	Longitude west (5)	Sounding (6)	Observed gravity (7)	International formula gravity (8)	Free air anomaly (9)	Bouguer anomaly (10)
		1952	° ′	° ′	m	gal	gal	mgal	mgal
164(c)	1	May 31	41-23.6	72-05.6	6	980.296	980.305	−9	−8
1793	2	June 2	41-14	71-41	35	.290	.291	−1	2
1794	3	June 3	41-12	72-04	95	.276	.288	−12	−5
1795	4	June 4	38-23	72-11	2975	979.986	.038	−52	172
1796	5	June 4	37-37	72-15	3232	.922	979.971	−49	195
1797	6	June 4	36-53	72-17	3477	979.884	979.907	−23	239
1798	7	June 5	35-34	72-30	4181	.748	.794	−46	269
1799	8	June 5	33-36	72-48	4904	.578	.628	−50	320
1800	9	June 5	32-34	73-03	5286	.488	.543	−55	344
1801	10	June 5	31-38	73-14	5306	.410	.467	−57	343
1802	11	June 5	30-22	73-32	4951	979.318	979.367	−49	324
1803	12	June 6	28-34	73-55	4663	.203	.228	−25	327
1804	13	June 6	27-34	74-03	4438	.138	.153	−15	320
1805	14	June 6	26-52	74-21	4410	.099	.102	−3	330
1806	15	June 6	26-06	75-17	4601	.014	.047	−33	314
1807	16	June 7	25-46	76-07	4854	978.925	979.023	−98	268
1808	17	June 7	25-44	76-33	4041	.912	.021	−109	196
1809	18	June 7	25-40	76-55	3403	.904	.016	−112	145
512(a)	19	June 8	25-05.2	77-20.1	7	979.030	978.975	55	56
1810	20	June 10	26-36	76-40	4352	978.987	979.082	−95	247
1811	21	June 10	27-40	76-13	4823	979.064	979.160	−96	268
1812	22	June 11	29-54	75-10	4374	.295	.330	−35	295
1813	23	June 11	31-00	74-55	3610	.425	.417	8	280
1814	24	June 11	31-51	74-45	4472	.449	.485	−36	301
1815	25	June 11	33-15	74-22	4471	.537	.599	−62	275
1816	26	June 12	34-50	73-36	3858	979.699	979.731	−32	259
1817	27	June 12	36-25	72-57	3523	.830	.867	−37	229
1818	28	June 12	37-21	72-27	3107	.910	.947	−37	197
1819	29	June 12	38-20	72-03	2918	.988	980.033	−45	175
1820	30	June 13	39-28	71-34	2256	980.105	.133	−28	142
164 (c)	31	June 13	41-23.6	72-05.6	6	980.297	980.305	−8	−7

Bouguer anomaly in milligals, assuming densities of 2.84 for the crustal rocks and 1.03 for sea water.

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Accuracy of Gravimetrically Computed Deflections of the Vertical

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Abstract—The rms (root mean square) error of the deflection of the vertical computed from gravity anomalies by the Vening Meinesz formula was calculated for two sets of hypotheses: (1) perfect knowledge of gravity within given radii, and none beyond; (2) ideal distribution of given numbers of gravity stations out to given radii, and no stations, or a uniform distribution, beyond.

The calculation for lack of gravity data beyond given radii was based on rms anomalies G_s, as found by Hirvonen, and on correlation of free-air anomalies determined from profiles in central USA.

The general formula employed to compute the rms error in the deflection is

$$\delta_n'' = \sqrt{\sum_{i=1}^{n} Q_i G_i \left\{ Q_i G_i + 2 \sum_{j=1}^{i-1} Q_j G_j r_{ij} \cos(\alpha_j - \alpha_i) \right\}}$$

where

$$Q_i = \frac{\csc 1''}{2\pi G} \int_{\alpha_1}^{\alpha_r} \int_{\psi_i}^{\psi_0} \frac{df(\psi)}{d\psi} \sin\psi \, d\psi \, d\alpha,$$

the effect of a one milligal anomaly for an arbitrary elemental area; r_{ij} is the coefficient of correlation between the mean anomalies of two elemental areas; and $(\alpha_j - \alpha_i)$ is the angle between two elemental areas subtended at the deflection point.

Assuming the rms point anomaly $G_0 = \pm 28$ mgal, the rms modulus of the deflection was found to be 6.0″. The rms effects of anomalies beyond given radii were found as follows: 3000 km, 1.2″; 2000 km, 1.7″; 1000 km, 2.2″; 500 km, 3.3″.

The rms geoid elevation computed in a similar manner was found to be ±21.3 m. The rms effects of anomalies beyond given radii were found as follows: 150°: ±5.1 m; 90°: ±7.6 m; 60°: ±11.0 m; 45°: ±11.5 m; 3000 km: ±11.9 m; 2000 km: ±13.4 m; 1000 km: ±17.2 m.

The discrepancy between the results obtained by these methods and those obtained by Cook in 1950 and 1951 using spherical harmonics is roughly proportional to the difference between the rms anomalies used.

Six ideal distributions, for which each gravity station makes an equal contribution to the deflection error, were computed out to 35°, and graphs constructed therefrom. The effects due to the errors of representation of these distributions were combined with those due to lack of gravity data beyond given radii to give a total uncertainty. For example, 200 stations out to 1000 km will give an rms error of 2.7″; to 2000 km, 2.0″; to 3000 km, 1.6″. For 50 stations, the corresponding figures are: 1000 km, 3.0″; 2000 km, 2.6″; 3000 km, 2.5″. A uniform distribution of one station to every 10° block will improve the rms error with 200 stations out to 1000 km to 1.2″; one to every 5° block will improve it to 0.8″.

Introduction—In a recent paper on the precision of the gravimetric determination of the geoid, *Hirvonen* [1956] found the error of representation and related functions for the mean anomalies of given-sized squares, and the covariance of the mean anomalies of 1°, 5°, and 10° squares; he also computed the uncertainty to be expected for gravimetric determination of the geoid for points in central United States and central Europe.

It is proposed in the present paper: first, to utilize the rms values of the mean anomalies of given-sized squares, and the correlation between mean anomalies of squares over given distances, to determine what uncertainty should normally be expected in the gravimetrically computed deflection of the vertical due to neglect of gravity data beyond any given radius; and second, to utilize the error of representation of anomalies for different sized squares to determine what uncertainty should be expected when a given number of stations are observed out to any given radius, and either no stations at all or a uniform distribution beyond this radius.

Gravity anomaly correlation—Hirvonen [1956]

computed the covariances of the mean isostatic anomalies of 1°, 5°, and 10° squares with centers a distance $d = hs$ apart

$$C_{s,d} = \frac{1}{n-h}\sum_{i=1}^{n-h}(\Delta g_i)(\Delta g_{i+h}) \tag{1}$$

The covariance is also known as the autocorrelation function. A related function is the coefficient of correlation

$$r = \frac{\sum_{i=1}^{n} x_i y_i}{\sqrt{\sum_{i=1}^{n} x_i^2 \sum_{i=1}^{n} y_i^2}} \tag{2}$$

If we set $x_i = \Delta g_i$, $y_i = \Delta g_{i+h}$ and substitute $n - h$ for n, we get:

$$r_{s,d} = \frac{\sum_{i=1}^{n-h}(\Delta g_i)(\Delta g_{i+h})}{\sqrt{\sum_{i=1}^{n-h}(\Delta g_i)^2 \sum_{i=1}^{n-h}(\Delta g_{i+h})^2}} \tag{3}$$

Divide both numerator and denominator by $n - h$

$$r_{s,d} = \frac{C_{s,d}}{[\text{rms}\ (\Delta g_i)]\ [\text{rms}\ (\Delta g_{i+h})]} \tag{4}$$

or, if n is large

$$r_{s,d} = \frac{C_{s,d}}{G_s^2} \tag{5}$$

It was decided to compute $r_{s,d}$ anew, rather than utilize the $C_{s,d}$ of Hirvonen, because squares much smaller than 1° had to be considered; the $r_{s,d}$ are more adaptable to variations in G_0 and G_s; and the $r_{s,d}$ are more convenient for the deflection computation.

The $r_{0,d}$ for point anomalies and $d < 80$ km were computed from profiles 1470 km and 1870 km long in south central United States. Point values were taken at 10-km intervals; these point values were interpolated from isoanomaly lines, and hence should give higher correlation values than actually exist. The $r_{0,d}$ for point anomalies and $d > 80$ km were computed from a profile across central USA 3050 km long.

In computing $r_{0,d}$, $\sum_{i=1}^{n}(\Delta g_i)^2$ was used in the denominator, to save recomputation for each d

$$r_{0,d} = \frac{n\sum_{i=1}^{n-h}(\Delta g_i)(\Delta g_{i+h})}{(n-h)\sum_{i=1}^{n}(\Delta g_i)^2} \tag{6}$$

where $h = d/10$ *km* for $d \geq 10$ km, and $h = d/1$ km for $d < 10$ km. (Point values taken at 1-km intervals).

To compute the $r_{s,d}$, consider first the covariance between the mean anomalies of two unequal areas. Assume the areas to be squares of side length ls and ks, $l > k$, and assume that the line joining the two centers a distance d apart bisects a side of each area. The covariance of the two large areas ls and ks, $C_{ls/ks,d}$, will be the mean of all the l^2k^2 covariances $C_{s,\sqrt{(d+hs)^2+(is)^2}}$ between the smaller component areas of side length s

$$C_{ls/ks,d} = \frac{1}{l^2k^2}\sum_{h=1-(l+k)/2}^{(l+k)/2-1} \cdot \sum_{i=1-(l+k)/2}^{(l+k)/2-1} A_h A_i C_{s,\sqrt{(d+hs)^2+(is)^2}} \tag{7}$$

$A = k$ when $|h|$ or $|i| \leq (l-k)/2$

$A = k - j$ when $|h|$ or $|i| = (l-k)/2 + j$, $0 \leq j \leq k-1$.

h summations are made parallel to the line joining the two centers, and i summations are made perpendicular to it.

The quantity is is nearly always much smaller than $d + hs$. If we assume $C_{s,\sqrt{(d+hs)^2+(is)^2}} = C_{s,d+hs}$, take the case $l = k$, and substitute $G_s^2 r_{s,d} = C_{s,d}$ and $G_{ks}^2 r_{ks,d} = C_{ks,d}$, then (7) reduces to

$$G_{ks}^2 r_{ks,d} = \frac{G_s^2}{k^2}\sum_{h=-k+1}^{k-1}(k - |h|) r_{s,d+hs} \tag{8}$$

which was the formula actually employed to compute $r_{ks,d}$, using G_{ks} and G_s found by *Hirvonen* [1956]. For areas of unequal size

$$r_{ls/ls,d} = \sqrt{r_{ks,d} \cdot r_{ls,d}} \tag{9}$$

which is also derivable from (7).

In (7), if $d = 0$, $l = k$:

$$G_{ks}^2 = C_{ks,0} = \frac{1}{k^4}\sum_{i=-k+1}^{k-1}(k - |i|) \cdot \sum_{h=-k+1}^{k-1}(k - |h|) C_{s,\sqrt{(hs)^2+(is)^2}} \tag{10}$$

which is the same as the equation given by *Hirvonen* [1956, p. 4].

Eq. (5) and (10) indicate that the coefficients of correlation $r_{s,d}$ and the mean square anomalies G_s are interdependent to the extent that if G_0 and a complete set of $r_{0,d}$ are given, the G_s should be all derivable. Hence it is, strictly speaking, inconsistent to use sets of G_s and $r_{0,d}$ derived

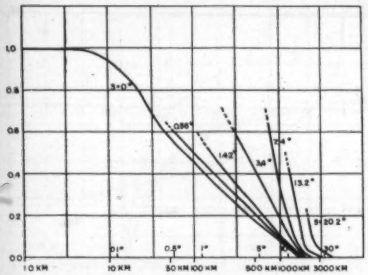

FIG. 1 – Coefficients of correlation of mean free-air anomalies for squares of side length s

from different sets of data, as has been done in this paper.

The $r_{10\text{km},d}$ were computed from the $r_{0,d}$ using G_0^2 and assuming $r_{1\text{km},d} = r_{0,d}$ in equation (8). Then all $r_{s,d}$ up to $r_{1^\circ,d}$ were computed from the $r_{10\text{km},d}$, and the larger $r_{s,d}$ from the $r_{1^\circ,d}$ for the areas of the compartments actually used later in the deflection computations. The area of these compartments was taken as equivalent to the areas of blocks of sides $\Delta\phi = \Delta\lambda$ at latitude 45°, approximately the average latitude of the anomalies from which Hirvonen computed the G_s. The coefficients of correlation are shown graphically in Figure 1.

Deflection error caused by omission of distant areas—In general, the deflection of the vertical at a point computed by the Vening-Meinesz formula from the mean anomalies of two small areas i and j will be

$$\delta''^2 = (Q_i\Delta g_i)^2 + (Q_j\Delta g_j)^2 + 2Q_i\Delta g_i Q_j\Delta g_j \cos(\alpha_j - \alpha_i) \quad (11)$$

where

$$Q_i = \frac{\csc 1''}{2\pi G}\int_{a_1}^{a_r}\int_{\psi_i}^{\psi_0}\frac{df(\psi)}{d\psi}\sin\psi\, d\psi\, d\alpha$$

α is azimuth and ψ is distance from the point; α_r, α_1, ψ_0, and ψ_i are area boundaries; and $df(\psi)/d\psi$ is the first derivative of Stokes' function, tabulated together with its integral by *Sollins* [1947].

To find the rms δ_n'' from n cases of areas i and j with the same Q_i and Q_j and the same angle apart

$$\text{Mean } \delta_n''^2 = Q_i^2(1/n)\sum(\Delta g_i)^2 + Q_j^2(1/n)\sum(\Delta g_j)^2 + 2Q_iQ_j(1/n)\cdot\sum(\Delta g_i\Delta g_j)\cos(\alpha_j - \alpha_i) \quad (12)$$

now $(1/n)\sum(\Delta g_i)^2 = G_i^2$, $(1/n)\sum(\Delta g_j)^2 = G_j^2$, and $(1/n)\sum(\Delta g_i\Delta g_j) = C_{i,j} = r_{i,j}G_iG_j$. If we add a third area k

$$\text{Mean } \delta_n''^2 = Q_i^2G_i^2 + Q_j^2G_j^2 + Q_k^2G_k^2 + 2Q_iQ_jG_iG_jr_{i,j}\cos(\alpha_j - \alpha_i) + 2Q_iQ_kG_iG_kr_{i,k}\cos(\alpha_k - \alpha_i) + 2Q_jQ_kG_jG_kr_{j,k}\cos(\alpha_k - \alpha_j) \quad (13)$$

and for n areas $i, j, \cdots, n$

$$\text{Mean } \delta_n''^2 = Q_i^2G_i^2 + Q_j^2G_j^2 + \cdots + Q_n^2G_n^2 + 2Q_jG_jQ_iG_ir_{i,j}\cos(\alpha_j - \alpha_i) + 2Q_kG_k[Q_iG_ir_{i,k}\cos(\alpha_k - \alpha_i) + Q_jG_jr_{j,k}\cos(\alpha_k - \alpha_j)] + \cdots + 2Q_nG_n\sum_{x=1}^{n-1}Q_xG_xr_{x,n}\cos(\alpha_n - \alpha_x) \quad (14)$$

or factoring out each Q_iG_i

$$\text{Rms } \delta_n'' = \sqrt{\sum_{i=1}^{n}Q_iG_i\left\{Q_iG_i + 2\sum_{j=1}^{i-1}Q_jG_jr_{i,j}\cos(\alpha_i - \alpha_j)\right\}} \quad (15)$$

This method of computing the rms δ'' was applied to the zone from $\psi = 0°.045 = 5$ km to $\psi = 35° = 3880$ km. The areas used were eight zones of equal $\int_{\psi_i}^{\psi_0}(df/d\psi)\sin\psi d\psi = 0.973$, divided into eight sectors, so that

$$Q = (\csc 1''/2\pi G)\int_0^{\pi/4}0.973\, d\alpha = 0.0256''$$

always.

The sum $\sum_{j=1}^{p-1}Q_jG_jr_{ij}\cos(\alpha_j - \alpha_i)$ is constant, and the sum $\sum_{j=p}^{i-1}Q_jG_jr_{ij}\cos(\alpha_j - \alpha_i)$ is cumulative, for each zone of eight compartments with $i = p, \cdots, p + 7$. A final advantage is that at the end of each zone the total effect out to that radius is obtained. The distance between areas was measured graphically, to obtain the coefficients of correlation.

For the central area, it was assumed that the rms anomaly was ±28 mgal, and that $r_{0,10\text{km}}$ was 0.95, which gave for the rms difference of anomalies across the central circle

$0.95 = (28 - q)(28 + q)/28^2$, $q = 6.5$ mgal, and the resultant gradient: $\partial\Delta g/\partial s = \sqrt{2}\,6.5/5 = 1.9$ mgal/km, whence $\delta_0'' = 0.105'' \times 5 \times 1.9 = 1.00''$. Since the $\cos(\alpha_j - \alpha_i)$ to this central area

TABLE 1 – *Computation of rms deflection*

n	Inner boundary		$\sqrt{\sum_{z=n}^{9} \delta_z''^2}$	δ_z''	$\sqrt{\sum_{z=0}^{n} \delta_z''^2}$	Outer boundary		n
	km	°	"	"	"	km	°	
0	0	0.000	5.98	.00	1.00	5	0.045	0
1	5	0.045	5.90	.95	1.38	13	0.119	1
2	13	0.119	5.82	2.40	2.78	35	0.313	2
3	35	0.313	5.30	2.54	3.76	91	0.817	3
4	91	0.817	4.65	2.44	4.49	232	2.08	4
5	232	2.08	3.96	2.51	5.04	562	5.06	5
6	562	5.06	3.22	2.24	5.52	1240	11.12	6
7	1240	11.12	2.30	1.66	5.77	2340	21.01	7
8	2340	21.01	1.59	1.34	5.92	3880	35.0	8
9	3880	35.00	0.86	0.86	5.98	20100	180.0	9

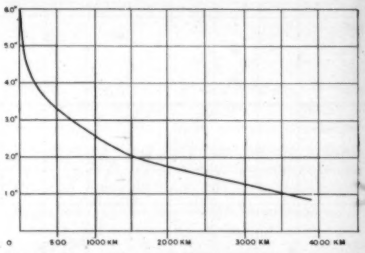

FIG. 2 – Rms error in gravimetrically computed deflections of the vertical with perfect knowledge of gravity out to given radii

of opposing compartments of equal $r_{i,j}$ cancel each other out in every case, δ_0'' is in effect random with respect to all other computed δ''.

The distant area beyond $\psi = 35°$ was divided into two zones within $\psi = 72°$ (for which $df/d\psi$ is zero) and two zones beyond 72°; the zones were divided into 30°blocks of $G_z = \pm 8.7$ mgal, assumed random with respect to each other. Then the rms deflection due to a zone containing n 30° blocks will be

$$\delta_z'' = \sqrt{n}\left(\frac{\csc 1''}{nG}\int_{\psi_i}^{\psi_0} G_z \frac{df}{d\psi}\sin\psi\, d\psi\right)$$

$$= \frac{\csc 1''\, G_z}{G\sqrt{n_{2\pi}(\cos\psi_i - \cos\psi_0)}}\int_{\psi_i}^{\psi_0}\frac{df}{d\psi}\sin\psi\, d\psi$$

$$= \frac{0.346}{\sqrt{\cos\psi_i - \cos\psi_0}}\int_{\psi_i}^{\psi_0}\frac{df}{d\psi}\sin\psi\, d\psi \quad (16)$$

where $n_{2\pi} = 27.9$ is the total number of 30° blocks (of average latitude 34°) in a hemisphere. The answer thus obtained was $\delta'' = 0.86''$. In Table 1, δ_z'' is the

$$\sqrt{\sum_{i=p}^{p+7} Q_i G_i\left\{Q_i G_i + 2\sum_{j=1}^{i-1} Q_j G_j r_{i,j}\cos(\alpha_j - \alpha_i)\right\}}$$

for each zone $i = p, \cdots, p+7$. The $\sqrt{\sum_{z=n}^{9}\delta_z''^2}$ is the rms error which should be expected due to perfect knowledge of gravity out to the inner boundary of the zone $z = n$, and none beyond this boundary. This rms error is shown graphically in Figure 2.

The $\sqrt{\sum_{z=0}^{n}\delta_z''^2}$ in Table 1 is the rms value which should be expected from computing the deflection from zero out to the outer boundary of the zone $z = n$. It should be comparable to the rms of several deflections found by actual computation.

Figure 3 shows the function $\sqrt{\sum_{z=0}^{n}\delta''^2}$ out to 400 km, together with the rms value out to 400 km of sixteen stations in south central United States computed by *Rice* [1952]. The latter curve is appreciably lower, but the theoretical curve $\sqrt{\sum_{z=0}^{n}\delta''^2}$ is based on $G_0 = \pm 28$ mgal, whereas for south central United States $G_0 = \pm 20$ mgal. Redrawing the theoretical curve for $G_0 = \pm 20$ mgal gives a much closer fit to the USC & GS values, which is improved further by changing the USC & GS mean ξ'' and η'', which are $+1.05''$ and $-0.45''$ for 400 km, to $0.0''$.

The quantitative evaluation of the correlation between anomalies of adjacent areas suggests a means to improve the accuracy of gravimetrically computed deflections by extrapolating anomalies from the last observed zone. The coefficients of correlation which are derived from rms anomalies should be applied with caution to actual observed anomalies, however, since $r_{0,d}$ is to some extent a function of the absolute magnitude $|\Delta g|$ of the anomaly. The magnitude of the

$$Q_i G_i \sum_{j=1}^{p-1} Q_j G_j r_{i,j}\cos(\alpha_j - \alpha_i)$$

terms indicate how much is to be gained by extrapolation; adding them to the zones to which j applies in the summations gives Table 2.

Inaccuracies of the methods used herein to compute the rms deflections include: (1) the use of $r_{z,d}$ and G_z based on different sets of gravity

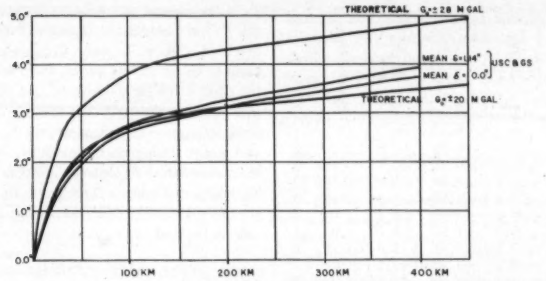

FIG. 3 – *Rms* numerical value for deflections of the vertical computed gravimetrically from anomalies out to given radii

TABLE 2 – *Improved rms deflection*

n	Inner boundary	$\sqrt{\sum_{z=n}^{9} \delta_z \eta^2}$
	km	"
0	0	5.98
1	5	5.90
2	13	5.42
3	35	4.78
4	91	4.11
5	232	3.28
6	562	2.54
7	1240	1.83
8	2340	1.22
9	3880	0.86

data; (2) assuming $r_{s,\sqrt{(d+hs)^2+(is)^2}} = r_{s,d+hs}$; (3) using interpolated in place of observed anomalies in computing the point anomaly correlations; and (4) using rather large compartments in computing the rms deflections. The last three inaccuracies should all cause the theoretical curve for $G_0 = \pm 20$ mgal to appear lower than the computed curve in Figure 3.

Geoid elevation error caused by omission of distant areas—A formula similar to (15) can be derived for the rms error in N, the displacement of the geoid from the reference spheroid

$$\text{Rms } N_n = \pm\sqrt{\sum_{i=1}^{n} R_i G_i \left\{ R_i G_i + 2 \sum_{j=1}^{i-1} R_j G_j r_{ij} \right\}} \quad (17)$$

where

$$R_i = \frac{R}{2\pi G} \int_{\alpha_1}^{\alpha_r} \int_{\psi_i}^{\psi_0} f(\psi) \sin \psi \, d\psi;$$

$f(\psi)$ is Stokes' function, tabulated together with its integral by *Lambert* and *Darling* [1936]. The term $\cos(\alpha_j - \alpha_i)$ does not appear because there is no directionality of effect of an anomaly in this case.

To save computing a new set of correlations, the same compartments as for the deflections were used out to 35°. Beyond 35°, more zones, divided into 30° blocks, were used: one to $\psi = 39°$, where $\Phi(\psi) = \int_0^{\psi} f(\psi) \sin \psi \, d\psi$ is a maximum; four of equal $\Delta\Phi = 0.1911$ to $\psi = 118°$, where Φ is a minimum; and two more to $\psi = 180°$. The rms effect of each zone, similar to (16)

$$N_z = \sqrt{n_z}\left(\frac{R}{n_z G} \Delta\Phi G_z\right) = \frac{RG_z}{G} \cdot \frac{\Delta\Phi}{\sqrt{n_{2\pi}(\cos\psi_i - \cos\psi_0)}} = 10.71 \frac{\Delta\Phi}{\sqrt{\cos\psi_i - \cos\psi_0}} \quad (18)$$

The N_z are summarized in Table 3.

The $\sqrt{\sum_{z=n}^{16} N_z^2}$ are shown graphically in Figure 4.

The rms elevation of ± 21.3 m is somewhat smaller than the rms of the elevations obtained by *Tanni* [1948], ± 26 m.

Comparison with results obtained by spherical harmonics—An interesting comparison can be made of the deflections and elevations summarized in Figures 2 and 4 with those obtained by *Cook* [1950, 1951] by an entirely different method. Cook's analysis assumes: (1) the variance τ_2 ($= G_{30}^2$) of 30° squares is 227 mgal², and the variance $\tau_1 + \tau_2$ of 10° square is 660 mgal²; (2) the world gravity field to the third harmonic has a variance of 90 mgal², and is known perfectly; (3) the rest of the gravity field can be expressed as a

TABLE 3 – *Computation of rms elevation*

n	Inner boundary	$\sqrt{\sum_{m=n}^{16} N_m^2}$	N_n	$\sqrt{\sum_{m=0}^{n} N_m^2}$	Outer boundary	n
	°	m	m	m	°	
0	0.00	±21.3	±0.02	±0.0	0.045	0
1	0.045	±21.3	±0.25	±0.3	0.119	1
2	0.119	±21.3	±0.69	±0.7	0.313	2
3	0.313	±21.3	±1.77	±1.9	0.817	3
4	0.817	±21.2	±3.98	±4.4	2.08	4
5	2.08	±20.8	±7.52	±8.7	5.06	5
6	5.06	±19.4	±10.38	±13.6	11.12	6
7	11.12	±16.4	±9.70	±16.7	21.01	7
8	21.01	±13.3	±6.28	±17.8	35.0	8
9	35.0	±11.7	±0.38	±17.8	39.0	9
10	39.0	±11.7	±3.82	±18.2	60.7	10
11	60.7	±11.0	±4.97	±18.9	71.4	11
12	71.4	±9.9	±4.97	±19.5	81.4	12
13	81.4	±8.5	±4.60	±20.1	92.6	13
14	92.6	±7.2	±3.17	±20.3	118	14
15	118	±6.4	±3.43	±20.6	148	15
16	148	±5.4	±5.43	±21.3	180	16

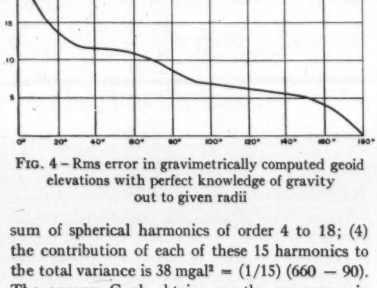

FIG. 4 – Rms error in gravimetrically computed geoid elevations with perfect knowledge of gravity out to given radii

sum of spherical harmonics of order 4 to 18; (4) the contribution of each of these 15 harmonics to the total variance is 38 mgal² = (1/15) (660 − 90). The answers Cook obtains are the rms errors in one component ξ'' of the deflection and in the elevation N with respect to the third-order spheroid corresponding to the gravity formula of *Jeffreys* [1943], which differs from the International formula as follows

$$\begin{aligned}\Delta\gamma = {} & +2.5 \pm 1.9 - (6.1 \pm 5.0)\, P_2 \\ & + (4.0 \pm 1.4) P_2^2 \cos 2\lambda \\ & + (1.30 \pm 0.68) P_3^2 \cos 2\lambda \\ & + (4.2 \pm 2.4) P_3^1 \cos \lambda \\ & + (0.46 \pm 0.26) P_3^3 \sin 3\lambda \end{aligned} \qquad (19)$$

P_2 is the second order Legendre polynomial and the P_n^m are associated Legendre functions of the first kind of $\sin\phi$. To make Cook's answers comparable to those in this paper, there must be added the effect of these differences, and the deflections only multiplied by $\sqrt{2}$. The variance of the second-order difference is 45.8 mgal²; of the third order, 40.5 mgal². Using these variances, we can apply the same method for orders 2 and 3 as did Cook for harmonics of Orders 4 through 18. In this method, the rms error in the deflection due to a harmonic of order n beyond radius ψ_0 is

$$\sigma(\xi_n'') = \frac{\csc 1''\, \sqrt{2 V_n n(n+1)}}{2G(n-1)} \cdot \int_{\psi_0}^{\pi} P_n^1(\cos\psi) \frac{df(\psi)}{d\psi} \sin\psi\, d\psi \qquad (20)$$

where V_n is the variance in the gravity anomalies due to the harmonic, and $P_n^1(\cos\psi)$ is the associated Legendre function of the first kind. Taking $\sigma(\delta'') = \sqrt{2}\sigma(\xi'')$, the results are set forth in Table 4.

The similar equation for the rms error in the geoid elevation

$$\nu(N_n) = \frac{R}{G}\sqrt{V_n} \int_{\psi_0}^{\pi} P_n(\cos\psi) f(\psi) \sin\psi\, d\psi \qquad (21)$$

where $P_n(\cos\psi)$ is the Legendre polynomial. The results are set forth in Table 5.

The discrepancies between the two solutions appear thus to be principally caused by the differences in the rms anomalies used. The reason for the contrary trends of the deflection and elevation comparisons does not seem readily apparent; perhaps Cook attributes too great a proportion of the variance to the low-order terms, or else the correlations used in this paper for distances beyond 15° or 30° are too low. The latter suggestion is inconsistent with the comparative ratios of 10°

TABLE 4 – *Comparison of deflections*

Item	ψ_0					
	0°	10°	15°	20°	25°	30°
Harmonics 4–18, $\sigma(\delta'')$, sec	5.9	2.4	1.5	1.3	1.1	0.8
Harmonics 2–18, $\sigma(\delta'')$, sec	7.4	4.4	3.7	3.2	2.7	2.4½
Results of this paper (Fig. 2), sec	6.0	2.4	1.9	1.6½	1.4	1.1
Ratio of results	1.2	1.8	2.0	1.9	2.0	2.2
Ratio of rms anomalies	$\sqrt{r_1 + r_2}/G_{10°} = 2.0$			$\sqrt{r_2}/G_{30°} = 1.7$		

TABLE 5 – *Comparison of geoid elevations*

Item	ψ_0			
	0°	10°	20°	30°
Harmonics 4–18, $\nu(N)$, m	±23.4	±7.8	±5.1	±3.3
Harmonics 2–18, $\nu(N)$, m	±54.2	±38.2	±28.8	±24.0
Results of this paper (Fig. 4), m	±21.3	±17.0	±13.6	±12.2
Ratio of results	2.5	2.3	2.1	2.0
Ratio of rms anomalies	...	2.0	...	1.7

and 30° rms anomalies; that is, Hirvonen's $G_{10°}/G_{30°} = 1.47$ indicates greater correlation than Cook's $\sqrt{\tau_1 + \tau_2}/\sqrt{\tau_2} = 1.65$. For blocks larger than 5°, both Hirvonen's and Cook's mean-square anomalies are based on the data of *Tanni* [1948]; the former used isostatic anomalies and the latter free-air anomalies. Tables 4 and 5 thus appear to indicate that the isostatic reduction has roughly the same effect as the third-order term in Jeffreys' formula. However, it is difficult to conceive of a mechanism whereby isostasy would account for effects of wave length greater than 30°. More likely is that, on the one hand, the assumption of zero correlation between 30° blocks is wrong: a small correlation persisting well beyond 30° will have considerable effect; while, on the other hand, the correlation indicated by the Jeffreys third-order terms is too large. In any case, more widespread gravity data are needed to give valid values for G_s.

The small values obtained by *Cook* [1950, 1951] for Harmonics 4 through 18 (first lines of Tables 4 and 5) show the usefulness of Jeffreys' harmonic formula to express the general gravity field. They do not, however, indicate the accuracies to be expected. To evaluate the actual rms errors, we must take into account the uncertainties ±1.9, ±5.0, ±1.4, etc. of the coefficients in Jeffreys' Eq. (19). Computing the second-order (9.7 mgal²) and third-order (12.35 mgal²) variances due to these uncertainties and treating them with (20) and (21), we get for the rms errors in the deflection: 2.2″, for $\psi_0 = 10°$; 1.6″ for 15°; and 0.9″ for 30°; and for the rms errors in the geoid elevation: ±19.3 m for 10°; ±14.1 m for 20°; and ±11.5 m for 30°.

These uncertainties should be comparable to those computed from the world wide gravity field for actual points. *Hirvonen* [1956] made such a computation for two points: one in North America, with dense gravity data out to 12°, and scattered data beyond, such as is represented by the Jeffreys' formula; and one in Europe, with dense data out to about 14°, and scattered data beyond. Comparing the uncertainties found by Hirvonen with values interpolated from those derived in the preceding paragraph gives the following ratios for $\psi_0 = 12°$: 1.94″/0.88″ = 2.2 and 18.3/10.4 = 1.8; for $\psi_0 = 14°$: 1.72″/0.82″ = 2.1 and 17.2/10.4 = 1.7; all again very close to the ratio 2.0 of the rms anomalies used.

Deflection error due to errors of representation of observed anomalies—Two types of distribution of gravity stations warrant consideration: first, one in which the density of the stations thins out as we move away from the point for which the deflection of the vertical is to be computed; and second, one in which there are gravity stations at regular intervals over the Earth. The first we shall call an 'ideal' distribution; the second, a 'uniform' distribution.

An ideal distribution of gravity stations is one for which a given number of stations will give a minimum error in the deflection, assuming them to be confined within a given radius. This ideal should be approached by having each observed anomaly represent as nearly square an area as possible, and by having each observed anomaly contribute equally to the total uncertainty of the deflection. A distribution giving this result is one in which the observed gravity stations are arranged in rings around the deflection point, such that the number of stations in each ring $n = [(\psi_0 + \psi_i)/(\psi_0 - \psi_i)]\pi$, where ψ_i and ψ_0 are the inner and outer boundaries of the zone represented by the ring; and such that the quantity $(F_s/n)\int_{\psi_i}^{\psi_0} df/d\psi \sin\psi \, d\psi$ is equal for all rings. In this expression $F_s = G_s E_s/G_0$, the rms uncertainty of the weighted mean of a single observed anomaly and zero: $\Delta g_s = \left(\frac{G_s}{G_0}\right)^2 \Delta g$, which *Hirvonen* [1956] derives as the best value to take as representative of an area.

Six distributions of gravity stations were computed out to 35°, all starting from $\psi_i = 5$ km = 0.045°. The rms error due to one station $\epsilon = \frac{F_s \csc 1''}{nG}\int_{\psi_i}^{\psi_0} \frac{df}{d\psi} \sin\psi \, d\psi$ is constant for each of the six distributions given in Table 6.

Curves of equal n are interpolated from these numerical values on Figure 5. The effect of the area within 5 km is assumed to be errorless.

The squares of the values given by the graph in Figure 5 can be added to the squares of those in Figure 2, which assume perfect knowledge

TABLE 6 – *Ideal distributions of gravity stations*

$\epsilon = 0.6''$			$\epsilon = 0.3''$			$\epsilon = 0.19''$		
ψ_0	Σn	$\sqrt{\Sigma \epsilon^2}$	ψ_0	Σn	$\sqrt{\Sigma \epsilon^2}$	ψ_0	Σn	$\sqrt{\Sigma \epsilon^2}$
°		″	°		″	°		″
0.30	4	1.22	0.20	5	0.69	0.155	6	0.45
1.2	9	1.89	0.6	11	0.99	0.43	13	0.67
3.7	15	2.37	1.5	18	1.29	1.00	21	0.85
12.0	21	2.78	3.5	26	1.59	2.1	30	1.06
35	27	3.16	8	34	1.84	4.0	40	1.24
			17	43	2.04	7.5	50	1.41
			35	52	2.24	13.5	61	1.55
						24	72	1.68
						42	84	1.82

$\epsilon = 0.10''$			$\epsilon = 0.06''$			$\epsilon = 0.024''$		
ψ_0	Σn	$\sqrt{\epsilon^2}$	ψ_0	Σn	$\sqrt{\Sigma \epsilon^2}$	ψ_0	Σn	$\sqrt{\Sigma \epsilon^2}$
°		″	°		″	°		″
0.120	7	0.26	0.100	8	0.17	0.080	11	0.08
0.273	15	0.39	0.298	18	0.24	0.133	24	0.12
0.554	24	0.50	0.364	29	0.31	0.212	38	0.15
1.02	35	0.59	0.62	41	0.36	0.325	53	0.17
1.76	47	0.68	1.01	54	0.42	0.48	69	0.20
2.90	60	0.77	1.57	68	0.48	0.69	86	0.22
4.58	74	0.85	2.35	84	0.53	0.96	104	0.25
7.04	84	0.93	3.40	101	0.58	1.32	124	0.27
10.7	104	1.01	4.84	119	0.63	1.77	166	0.29
16.0	120	1.09	6.75	138	0.68	2.34	189	0.31
23.5	137	1.16	9.25	158	0.73	3.05	213	0.33
34.0	154	1.23	12.5	179	0.77	3.90	239	0.35
			16.8	200	0.82	4.96	265	0.38
			22.3	222	0.86	6.2	293	0.40
			29.3	245	0.91	7.7	322	0.42
						9.5	352	0.44
						11.6	384	0.46
						14.0	417	0.48
						16.8	452	0.50
						20.0	488	0.52
						23.8	524	0.54
						28.2	561	0.56
						33.2	600	0.58
						39.0	639	0.59

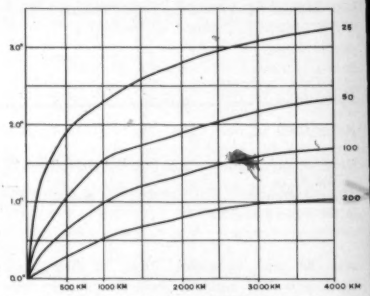

FIG. 5 – Rms error in gravimetrically computed deflections of the vertical due to errors of representation of point anomalies

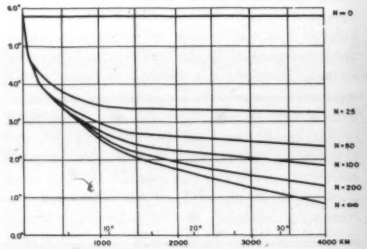

FIG. 6 – Rms error of gravimetrically computed deflections of the vertical due to errors of representation of point anomalies plus lack of gravity data beyond given radii.

($n = \infty$), to give the combined uncertainty for ideal distributions from $n = 0$, which is constant at 5.9″, to $n = \infty$ (Fig. 6).

Similar ideal distributions of stations for computation of the geoid elevation N can be constructed by substituting the condition that $(F_s/n)\int_{\psi_1}^{\psi_0} f \sin\psi \, d\psi$ is equal for all rings.

To compute the effect of a uniform distribution of gravity stations beyond a given radius, we can utilize the same zones that were used to compute the effect of neglecting the distant areas, and adapt (16) and (18) by substituting the appropriate error of representation F_s for G_s and the $n_{2\pi}$ of whatever spacing we consider for $n_{2\pi} = 27.9$ of the 30° blocks. For 10° spacing, F_s is 11.4 mgal and $n_{2\pi} = 251$; for 5° spacing, F_s is 13.0 mgal and $n_{2\pi} = 1006$. Using these values in (16) and (18) gives the figures in Table 7.

Curves for perfect knowledge of gravity within given radii and these distributions beyond the radii can be drawn similar to Figure 2. Also the effects of ideal distributions can be combined with these curves to give graphs similar to Figure 6. Thus, for example, 200 stations out to 1000 km from the deflection point, with 10° spacing beyond will give an rms error of $\sqrt{0.55^2 + 1.04^2} = 1.19''$; with 5° spacing beyond will give an rms error of $\sqrt{0.55^2 + 0.56^2} = 0.78''$.

Discussion—The principal defect of this in-

TABLE 7 – *Rms error due to uniform distributions beyond given radii*

5° spacing				n	ψ_i	10° spacing			
δ_ξ''	$\sqrt{\sum_{i=1}^{9} \delta_{\xi i}^2}$	N_ξ	$\sqrt{\sum_{i=1}^{9} N_{\xi i}^2}$			δ_ξ''	$\sqrt{\sum_{i=1}^{9} \delta_{\xi i}^2}$	N_ξ	$\sqrt{\sum_{i=1}^{9} N_{\xi i}^2}$
"	"	m	m			"	"	m	m
1.44	1.66	±0.3	±2.9	5	232 km	2.61	3.02	±5.2	±9.8
0.67	0.83	±0.3	±2.9	6	562 km	1.25	1.54	±5.0	±8.5
0.37	0.49	±0.2	±2.8	7	1240 km	0.68	0.89	±4.0	±6.8
0.24	0.32	±0.1	±2.8	8	2340 km = 21.01°	0.44	0.58	±1.9	±5.4
...	0.21	...	±2.8	9	... 35°	...	0.37	...	±5.1

vestigation is its reliance on the values used for rms anomalies G_s, which are closely correlated with that for a point anomaly G_0. Of probably minor effect on the results obtained is the different bases of the G_s and $r_{0,d}$ used.

Both Jeffreys' and Tanni's data, as adapted by Cook, indicate that the G_0 of ±28 mgal used herein is too low for the world as a whole. But, on the other hand, it can be too high for extensive areas such as the south central United States, where $G_0 = \pm 20$ mgal for an area 1500 × 1800 km. Ideally, the rms anomalies and covariances (or coefficients of correlation) should be computed from as widespread an assortment of observed gravity anomalies as possible. Then the G_s and $r_{s,d}$ or $C_{s,d}$ should be computed from these G_0 and $C_{0,d}$ or $r_{0,d}$, using adaptations of formulas (7)–(10). Another possibility is integral expressions in place of (15) and (17), which perhaps could lead to a more efficient method of numerical evaluation.

For purposes of extrapolation and interpolation of gravity anomalies, more study is needed of the correlation as a function of the absolute value of an anomaly. As $|\Delta g|$ increases, $C_{0,d}$ increases, but not at as fast a rate, so that $r_{0,d}$ decreases.

This paper has practical value in that it gives a more general estimate of the magnitude of the errors to be expected from gravimetric computation of the geoid than those previously made. Investigations along the line of comparing gravimetric with astro-geodetic deflections for points in Europe and the Central USA tend to give more optimistic answers. *Cook* [1950, 1951] also gets answers seemingly more optimistic, because of the tacit assumption that Jeffreys' third-order gravity formula is error-free with respect to the International formula.

As previously suggested, further analysis of the frequency distribution and correlation of anomalies is needed. To test the validity of distributions considered, (but not to make practical application of the gravimetric method), particular attention should be given to places where exceptionally large deflections and anomalies make it difficult to fit the data to a statistical model.

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Extrapolation of Geomagnetic Field Components Along a Radius from the Center of the Earth

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Abstract—An approximate method of extrapolating geomagnetic field components is presented in which a very small amount of data is required to effect the continuation. From intensity values at two points lying on a common radius from the center of the Earth, an attenuation factor is obtained which is used in an exponential formula to extrapolate to additional collinear points.

Introduction—With data taken on a single spherical surface, the components of the geomagnetic intensity **F** may be extrapolated either upward or downward by means of spherical harmonics [*Vestine* and others, 1947] or by a Taylor series [*Zmuda* and *McClung*, 1955]. If data are available at points lying on a common radius from the center of the Earth, the following approximate method, derived from spherical harmonics, may be useful.

Method of extrapolating components—In regions that are outside sources of magnetism, the components of the geomagnetic intensity **F** may be expanded in a series of solid spherical harmonics. In polar coordinates r, θ, and ϕ, with origin at the Earth's center, the respective series are

$$X = \sum_{n=1}^{\infty} \sum_{m=0}^{n} \left(\frac{a}{r}\right)^{n+2} \frac{\partial}{\partial \theta} f_n^m(\theta, \phi) \qquad (1)$$

$$Y = -\sum_{n=1}^{\infty} \sum_{m=0}^{n} \left(\frac{a}{r}\right)^{n+2} \frac{1}{\sin \theta} \frac{\partial}{\partial \phi} f_n^m(\theta, \phi) \qquad (2)$$

$$Z = -\sum_{n=1}^{\infty} \sum_{m=0}^{n} (n+1) \left(\frac{a}{r}\right)^{n+2} f_n^m(\theta, \phi) \qquad (3)$$

where X, Y, and Z are respectively the northern, eastern, and downward components; a is the radius of the Earth; and $f_n^m(\theta, \phi)$ is a spherical surface harmonic of degree n and order m.

Consider now the variation with altitude of a field of the Z component that is representable by a single harmonic of degree n. This change with height h may be written as

$$\left(\frac{a}{r}\right)^{n+2} = \left[\left(1 + \frac{h}{a}\right)^{a/h}\right]^{-(n+2)(h/a)} \qquad (4)$$

where $r = a + h$.

For small values of h/a, (4) becomes

$$\left(\frac{a}{r}\right)^{n+2} = e^{-(n+2)(h/a)} \qquad (5)$$

since

$$\left(1 + \frac{h}{a}\right)^{(a/h)} \cong e \qquad (6)$$

where e is the base of the natural logarithm.

With the aid of (5), Eq. (3) may be written for points on a common radius, as

$$Z(h) = -\sum_{n=1}^{\infty} \sum_{m=0}^{n} Z_{n,m} e^{-\lambda_n h} \qquad (7)$$

where $\lambda_n = (n+2)/a$ and $Z_{n,m}$ is that part of the total value of Z which is associated with the surface harmonic of degree n and order m.

TABLE 1 – *Extrapolation of Z to height seven miles; intensity values in gammas*

Geographic colatitude	Extrapolated value	
	By exponential formula	By spherical harmonics
° ′		
40	46,842	46,843
40 30	46,510	46,507
41	46,168	46,166
41 30	45,823	45,824
42	45,476	45,475

To determine the various λ_n's in (7) requires a harmonic analysis. However, an approximate formula may be obtained under the assumption that the variation with altitude is adequately characterized by the use of a single λ; λ may be considered to be an average exponential attenuation coefficient.

With this approximation, (7) becomes

$$Z(h) = Z_0 e^{-\lambda h} \qquad (8)$$

where Z_o is the total value of Z at a point on the surface $h = 0$.

Thus, with (8), if Z is known at two points on the vertical axis, λ may be obtained and then used to compute Z at additional, collinear points.

Calculations were made with a simple field represented with spherical harmonics by

$$Z(r,\theta) = 61{,}140\left(\frac{a}{r}\right)^3 P_1(\cos\theta) + 380\left(\frac{a}{r}\right)^4 P_2(\cos\theta) - 459\left(\frac{a}{r}\right)^5 P_3(\cos\theta) - 460\left(\frac{a}{r}\right)^6 P_4(\cos\theta) + 144\left(\frac{a}{r}\right)^7 P_5(\cos\theta) - 40\left(\frac{a}{r}\right)^8 P_6(\cos\theta) \quad (9)$$

where $P_n(\cos\theta)$ is a Légendre polynomial of degree n.

The field in (9) is the axisymmetric part of the field computed by *Vestine* and others [1947] in their harmonic analysis of the world charts.

From (9), Z was computed at two points on a common radius. One point is on the surface of the Earth; the other, at an altitude of one mile. With these two Z values an average λ was obtained from (8), an equation which was also used to extrapolate to an altitude of seven miles. The results of the extrapolation are shown in Table 1; they are very good for this simple field which is dominated by the behavior of the first term, the dipole term.

In place of (8) one could use as an approximate formula

$$Z = Z_0\left(\frac{a}{r}\right)^{n+2} \quad (10)$$

and obtain, in a manner similar to that used with (8), an average n for use in the extrapolation. Here, however, there is the disadvantage that distances to the center of the Earth are required; in (8) a difference between distances to the center is used.

With a procedure similar to that applied in obtaining (8), approximate formulas may be obtained for extrapolating X and Y along a common radius. These equations are

$$X(h) = X_0 e^{-\beta h} \quad (11)$$

and

$$Y(h) = Y_0 e^{-\gamma h} \quad (12)$$

where X_o and Y_o are the total values of the respective components at a point on the surface $h = 0$; β and γ are average exponential attenuation coefficients.

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Sky Temperatures in the Imperial Valley of California

C. F. Kelly, T. E. Bond, and N. R. Ittner

Abstract—The cloudless sky in the Imperial Valley is shown to have possibilities as a heat sink for cooling livestock and structures. Measurements with a directional radiometer and other instruments indicated that a point in the north sky 60° above the horizon is usually as cool as, or cooler than, other parts of the sky. North sky temperatures averaged 20° to 30° lower than air temperatures near the ground. The correlation of observed sky temperatures with sky temperatures calculated by Brunt's empirical equation from ground observations was 0.58, highly significant.

Introduction—For a large part of the year much of the area of the world has a climate too hot for economical growth and production of European breeds of cattle. While an animal may lose heat by any of the usual modes of heat transfer—conduction, convection, radiation, and evaporation—cooperative studies by the U.S. Department of Agriculture and the University of California at the University's Imperial Valley Field Station at El Centro, have indicated that protection from radiation from Sun, ground, and other parts of the surround may offer the most economical method of lowering the environmental heat load on the animals [*Kelly* and *Ittner*, 1948; *Kelly, Bond* and *Ittner*, 1950; *Bond, Kelly* and *Ittner*, 1954]. Significant increases in daily gains of cattle have been produced by the construction of shades and corrals that reduce the radiant heat load from the Sun [*Ittner, Bond* and *Kelly*, 1954, 1955].

It seemed to the writers that possibly the full opportunities of radiation cooling to the sky had not been taken advantage of by agricultural engineers in the design of livestock shelters in hot climates. In connection with the studies at El Centro a series of observations of sky radiosity were taken over the period 1946 to 1956. (Radiosity is defined as the total quantity of radiant energy leaving a surface per unit time per unit area; it may be emitted, reflected, or transmitted energy.) Some of these observations are presented in this paper.

Instrumentation—Various investigators have reported on sky radiosities and effective sky temperatures. For the most part these studies have been made in cold areas, and several types of radiometers have been used. Their objectives were usually to determine the possibilities of heating by radiation exchange with the sky, rather than cooling [*Stoll* and *Hardy*, 1955]. It is often difficult to compare one set of results with another because of different instrumentation. In the El Centro observations various instruments were used for simultaneous observations so that comparisons could be made. Instruments used were: (1) total hemispherical radiometer [*Gier* and *Dunkle*, 1951]; (2) Eppley pyrheliometer [*Woertz* and *Hand*, 1941; *McDonald*, 1951]; (3) Gier directional radiometer [*Kelly, Bond*, and *Lorenzen*, 1949]; (4) Hardy dermal radiometer [*Hardy*, 1934], and (5) globe thermometer [*Bedford* and *Warner*, 1934; *Bond* and *Kelly*, 1955]. Each of these instruments has a different field of view, varying response to uneven radiosities within the field of view, and different sensing-element spectral absorptions. Several of the portable instruments used in the field studies in the Imperial Valley are shown in Figure 1. The Eppley pyrheliometer and total hemispherical radiometer both have half-space fields of view but differ in absorption characteristics. The Gier directional radiometer and Hardy dermal radiometer have similar absorption characteristics, but the former has a field of view, controlled by its 16° solid-angle cone of opening and the shape of its sensing element, slightly greater than the Hardy dermal radiometer. The latter has a polished collecting cone of about 12° solid angle. The globe-thermometer has a spherical field of view, of course, and its absorption depends upon the color and nature of the paint coating.

The differences in response of the various instruments to the same thermal radiation environment are shown in Figure 2, where observations on July 23, 1956, are plotted for globe thermometer, total hemispherical (plate) radiometer, Gier directional radiometer, and Eppley pyrheliometer. Air and soil-surface temperatures are also included, the latter indicating stored radiant energy. The soil-temperature record was obtained from a long capillary temperature recording instrument with

FIG. 1 – Portable radiation measuring instruments: globe thermometer, directional radiometer, portable potentiometer, and total hemispherical (plate) radiometer

its $\frac{1}{4}$-inch-diameter bulb covered with soil to a depth of $\frac{1}{16}$ inch.

The Eppley pyrheliometer and the total hemispherical radiometer in general give parallel responses, but the Eppley response, because it measures only the short-wave solar and diffuse energy, is only 60 to 65 pct of the response of the total radiometer, during midday.

The response of the Gier directional radiometer, pointed at the north sky, 60° above the horizontal, bears little relation to the two hemispherical instruments. The difference was most pronounced between 12h 00m and 13h 00m, when the sky became overcast, light clouds covering both the Sun and the north sky. The readings of the two hemispherical instruments lowered considerably, while that of the directional radiometer increased.

The other three responses, measured in terms of temperature—globe thermometer, soil surface, and air—are each the result of the balancing of heat transfer by radiation, convection, conduction, and evaporation and condensation. For these measurements to be indicators of solar and sky radiation, the velocity of air flow must be considered. This can be done approximately for the globe thermometer by methods previously described [*Bedford* and *Warner*, 1934; *Bond* and *Kelly*, 1955]. However, the spherical mean radiant temperature is entirely nondirectional and will not be considered in this report.

The Gier radiometer, because of its directional properties, portability, and ruggedness as a field instrument, was used to collect the data from the north sky, and the other instruments were used to supplement and describe the general sky and ground radiosities.

Radiosity variation of clear sky—As summarized by *Pleijel* [1954] in reporting the work of others, the temperature of a clear sky "results in a minimum at a compass point opposite to that of the sun and approximately at right angles to the direction of the Sun." This means that the lowest temperature 'cold sink' available for absorbing radiant energy from objects on the Earth's surface (and from the Earth itself) is constantly changing position. For a hemispherical building, such as an igloo, it will make little difference where in the sky this cold area is. But for a rectangular building, such as a livestock shelter, where the problem is to cool the animals directly by long-wave radiation

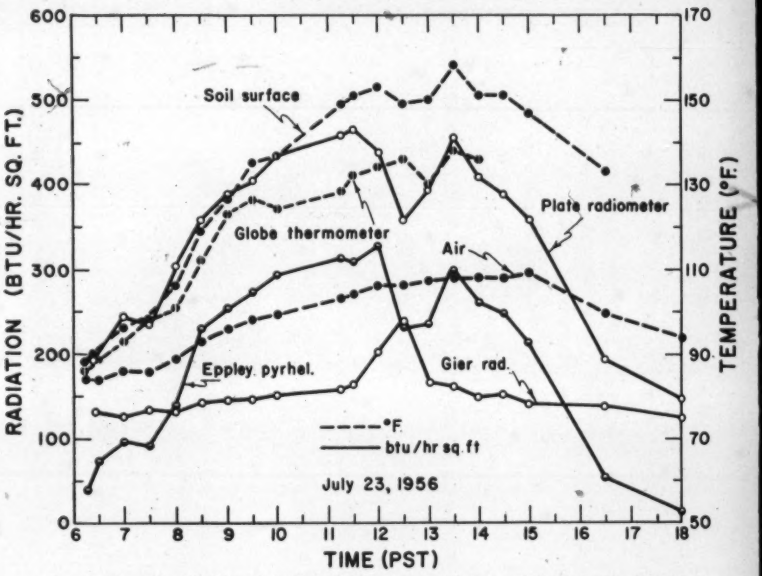

FIG. 2 – Responses of total hemispherical (plate) radiometer, Eppley pyrheliometer, Gier directional radiometer pointed at north sky, and globe thermometer, with air and soil surface temperatures, on a clear day

exchange between animal and sky, and at the same time keep solar and shade radiation to a minimum, we must have one area in the sky on which to base our design. It would not be practical to design a moving opening that would be able to follow the cold area. So we must select a field of view and obtain our data for it.

Many traverses with the Gier directional radiometer indicated that azimuth orientation had little effect upon sky radiosity throughout the hot part of the day if the instrument opening received no direct beam energy from the sun and the sky was free of clouds. But angle of elevation above the horizon was important; an angle of 60° was usually the 'coldest.'

In Figure 3 a series of traverses with the Gier directional radiometer in north-south and east-west orbits is shown for three different times on a cloudless day, April 27, 1949. At 12h 00m, when the radiometer target was almost as specified by Pleijel, the observations indicated the lowest sky radiosity. The radiosity of the north sky target at the point 60° above the horizon, as observed, was somewhat higher at 10h 00m and 14h 00m than at noon. The same inference can be made for the east-west traverse. It is interesting to note *Brooks'* [1951] finding that, for nocturnal radiation, 55° above the horizon represented the average (but not the lowest) back radiation to the Earth on clear nights. He also used a Gier radiometer of an earlier design.

Cloud cover and sky radiosity—With cloudless skies the radiosity of the north sky, 60° above the horizon varies little during the hot part of the day, as shown in the upper part of Figure 4 for August 10, 1955. The total hemispherical radiation, on the other hand, varied with sun elevation and azimuth.

The following day, August 11, with similar air temperature, the sky radiosity varied greatly during the forenoon, because of changes in the amount and position of clouds. Between 08h 30m and

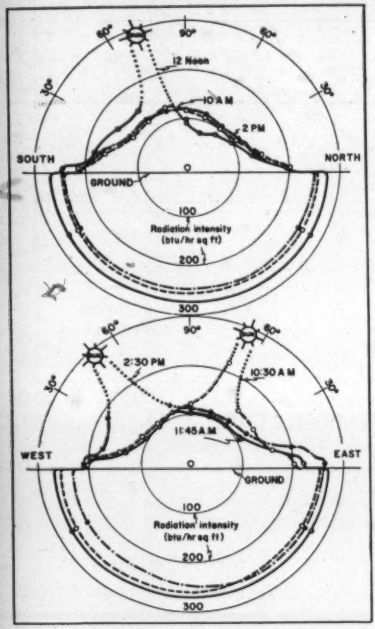

FIG. 3 – Traverses by Gier directional radiometer in north-south (top) and east-west (bottom) directions at three different times of day. Note low radiation intensity of sky (less direct Sun) as compared with ground.

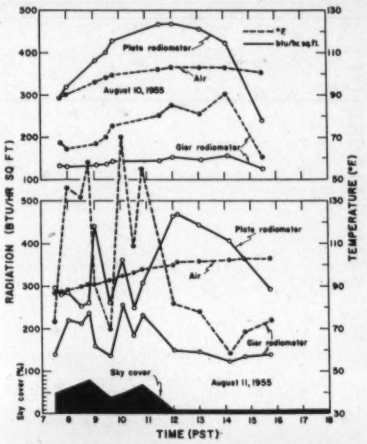

FIG. 4 – Effect of clouds on radiosity and effective temperatures of sky as measured by total hemispherical (plate) radiometer and Gier directional radiometer pointed at north sky; upper, clear day; lower, cloudy day.

09h 00m the sky was 70 to 80 pct covered by clouds, obscuring both the Sun and the north sky. The hemispherical radiometer reading lowered, and that of the directional radiometer (north sky) increased. At 09h 00m the clouds moved away from both the Sun and the north sky, and although the sky was still 50 pct obscured, the hemispherical radiation increased rapidly and the north sky radiation decreased. At 09h 30m a cloud again obscured the Sun, but the north sky remained clear. At 10h 00m the Sun was revealed but the north sky obscured; this change was also measured by the instruments. In the afternoon the entire sky cleared to less than ten per cent cloud cover, and both the hemispherical and north sky radiosities followed the preceding day's pattern.

Observed sky temperature versus air temperature—

In Figure 4 north sky 'temperature' is also given. This is calculated from the sky radiosities, using an emissivity for the sky of 1.0. It can be seen that on the clear day (August 10) north sky temperatures ranged from 23° lower than air temperature at 18h 00m to 13° lower at 14h 00m and 40° lower at 15h 30m. On the morning of the cloudy day (August 11) sky temperature varied erratically in the forenoon, increasing to high levels when a cloud reflected or radiated energy into the radiometer opening, but in the afternoon followed the previous day's course.

In the Imperial Valley the period considered to be depressing to livestock gains and production because of temperature is June through September. In Figure 5 a series of 116 north sky temperatures, observed with the Gier directional radiometer, has been plotted against air temperatures obtained simultaneously 42 inches above the ground. All observations were made between 10h 00m and 17h 00m on cloudless days (less than ten per cent cloud cover), during the months July to September. A linear regression curve has been fitted to these points. Its equation is

$$t_s = -81.9 + 1.5\, t_a$$

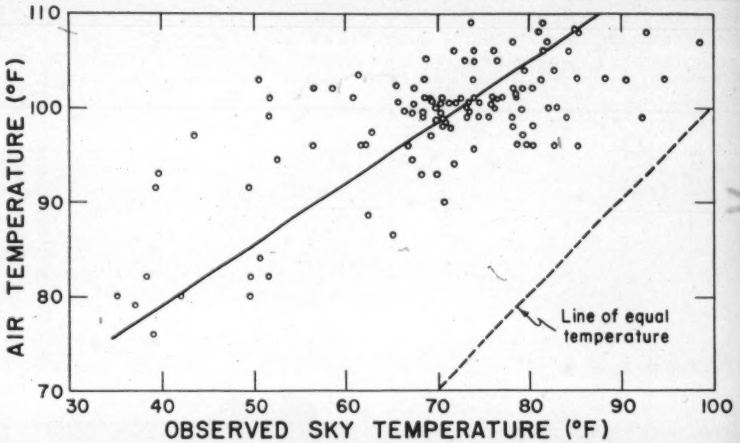

FIG. 5 – Relation of air temperature at ground to effective north sky temperature 60° above horizon

where t_s is the temperature of the sky and t_a the temperature of the air. The correlation coefficient is 0.74. A difference of about 28° between air and sky is available as a cooling sink at an air temperature of 100°, and of about 22° at 110°F.

Observed and calculated sky temperatures—In predicting sky temperatures from ground observations with instruments other than radiometers, it is evident that more than air temperature should be used to describe the radiating properties of the atmosphere. Water vapor, gas content, dust particles, air mass—all contribute to the absorption, back radiation, reflection, or transmission of radiant energy in the atmosphere. *Brunt* [1939] has suggested a possible method of calculating incoming radiation from observations of air temperature and vapor pressure at the ground by use of the empirical formula $R = \sigma T^4(a + b\sqrt{e})$, where R is the incoming radiation (Btu/hr sq ft), σ is the Stefan-Boltzmann radiation constant, T is the temperature of the Earth (°R), e is the mean monthly local vapor pressure of the air at the Earth's surface in millibars, and a and b are constants. Using Brunt's value of 0.55 for a and 0.056 for b, and values for e from surface readings at the time of the radiometer observations, we have made these calculations and plotted the calculated against observed results in Figure 6. The equation of the regression line is

$$t_o = 13.7 + 0.88\, t_c$$

where t_o is the observed sky temperature and t_c the calculated sky temperature. The correlation coefficient is 0.58. Other investigators [listed by *Goss* and *Brooks*, 1956], have suggested different values for the constants in Brunt's empirical equation, but none were found to give calculated results as close to the observed as these.

Imperial Valley cloud cover—It is apparent that under Imperial Valley conditions the extent of cloud cover is the main factor controlling north sky temperatures. In Figure 7 are given the daily percentages of cloud cover at 14h 00m for the month of August (Imperial Valley's hottest month) for the six-year period 1949 to 1954. These data were obtained from the Naval Air Station near El Centro, about 15 miles west of the University's field station. The large number of cloud-free days indicates a fairly reliable sink for radiation cooling. The junior author has observed also that even when the south hemisphere may be fairly cloudy, the north sky may be clear, because the clouds appear to form in the area towards the Gulf of California.

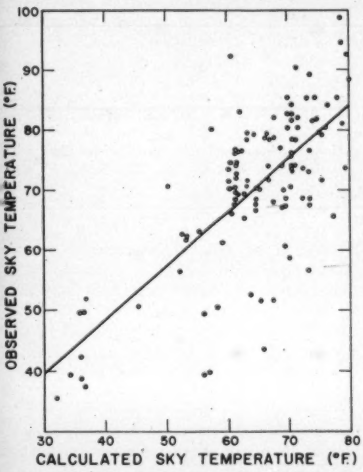

FIG. 6 – Relation of observed to calculated sky temperatures, using *Brunt's* [1939] empirical formula

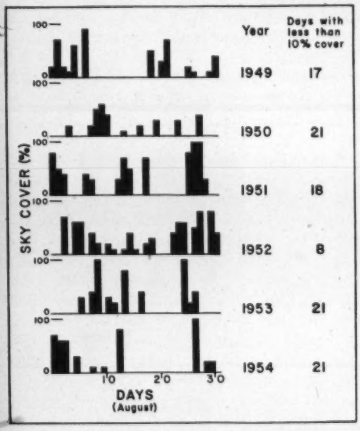

FIG. 7 – Daily cloud cover in August at 14h OOm, Imperial Valley, for period 1949 to 1954

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Photography of Submerged Vertical Structures*

RAYMOND F. MCALLISTER

Abstract—A device is illustrated and described with which photographs of the vertical walls of the La Jolla Submarine Canyon were obtained to a depth of 625 ft. Brief description of a number of the photographs is given, and photographs are reproduced. It is concluded that such an apparatus can provide pictures of sheer underwater scarps, reef faces, and, with suitable modifications, of dams, breakwaters, and bridge supports.

Introduction—During an investigation, undertaken by H. B. Stewart, to determine the geology of the La Jolla Submarine Canyon (Fig. 1) it became desirable to obtain photographs of the walls below diving depth [*Shepard*, 1949] to learn, if possible, something of the nature of the bedrock, sediment veneer, and organic incrustation. Since in many places the walls of this canyon are vertical and even overhanging, some method differing from those in the literature was needed to obtain pictures. After experimentation, the apparatus described below was developed by the author. Good photographs were obtained at a depth of over 600 ft.

The apparatus—Figure 2 shows the apparatus and method of suspension. Considerable modification can be made in size and material without impairing the usefulness of the device. The trip nose operates the camera upon contact with hard bottom by compressing a normally extended spring in the nose and allowing the cable within to become slack. The release mechanism of the camera case operates when unloaded; thus, a slack cable trips the camera and fires the flash bulbs which are electrically synchronized with the shutter. An NDRC underwater camera case, employing the German-made Robot camera, was used [*Ewing* and *Worzel*, 1942]. The canvas sail serves to keep the camera headed in the direction of the boat's travel and hence into the canyon wall. Suspension of the device forward of its center of resistance in a manner similar to a windvane helps maintain the required orientation.

The flash bulbs used were unprotected, types SM, SF, and #5. They were pretested for implosion by submerging them to a depth of more than 1000 ft before use, and gave adequate light for a camera-to-subject distance of more than 16 ft. Various inclinometers were used to indicate the vertical in the finished photographs, but results were rather unsatisfactory. Observations by divers with self-contained underwater breathing apparatus during early tests in 80 ft of water revealed that the device was very nearly horizontal at the moment of contact.

An attempt was made to obtain stereo photographs of the canyon walls by mounting two camera cases side by side and tripping them simultaneously. The picture separation was too great, however, to permit stereo viewing of the photographs.

For horizontal photography, most underwater camera cases may be used in a modification of the frame herein described, although one holding a camera with a larger negative size would be desireable.

Operation—A small boat with good speed control ahead and astern, equipped with a power winch, is most satisfactory. A DUKW was used with great success.

Ranges, determined by two objects of fixed and known location kept in direct line with each other, were selected. Using a comparatively accurate bathymetric chart of the canyon, areas of interest crossed by certain ranges were selected for survey. Using predetermined sextant angles and the ranges, it was possible to lower the apparatus to the required depth in the middle of the submarine canyon, with the trip nose directed toward a precise location on the canyon wall. The DUKW moved forward slowly during lowering, thus maintaining the orientation. Contact with the canyon wall was determined by the sudden tension in the wire rope, at which time the clutch on the winch was 'slipped' and the DUKW thrown into reverse. After the apparatus was free of potential snags it was retrieved, recocked, and new bulbs were inserted readying it for another lowering. With the DUKW on the range, a sextant angle was recorded at the moment of contact with the canyon wall. Proof of the accuracy of this

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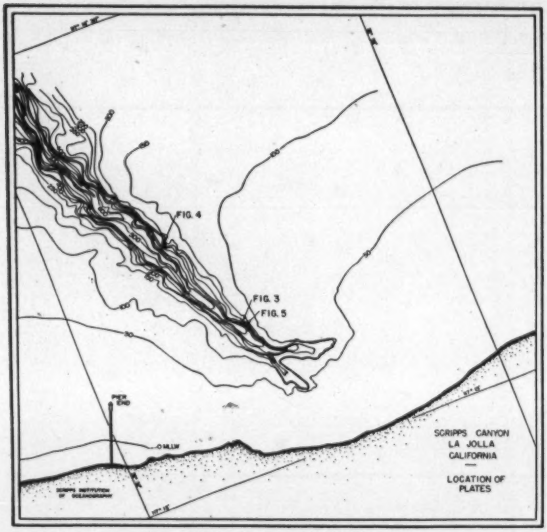

FIG. 1 – Index to location of photographs

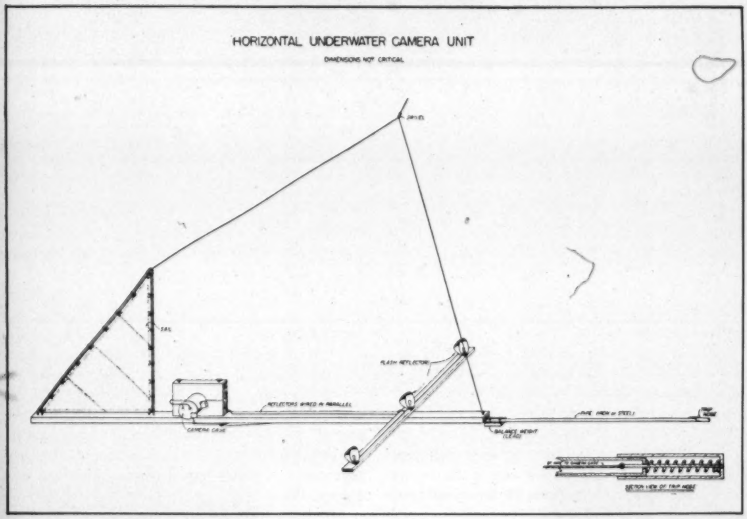

FIG. 2 – The horizontal underwater camera unit

FIG. 3 – Narrow ledge with nearly sheer rock face behind it; this area rephotographed one year later, showed no change in organisms or sediment cover; 300 ft deep, NW wall, Scripps Canyon; area about 3.5 ft square; vertical black line is suspending wire rope; photo data: f 5.6, $\frac{1}{100}$ sec, one SF flash bulb, Plus X film, camera to subject about 7.5 ft.

method of positioning is shown by two photographs taken one year apart which include the same area of the canyon wall while registering only a few minutes of angle difference at contact and very nearly the same depth by the amount of cable out (see below).

Adjustment of focus must be made to take into account the difference between the refractive indices of water and air (which also much reduces the field of view). For accurate focus, the camera should be set for 75 pct. of the underwater distance from lens to subject. A wide-angle lens effectively increases the field of view of the camera.

Results of the survey—From 88 lowerings made in 1952, 57 printable negatives were obtained from depths of 95 to 625 ft. These photographs, taken with a camera-subject distance of 7½ ft, covered an area approximately 3½ ft square. When sloping walls were photographed the area was much increased.

Most of the photographs show rock in various attitudes. Bedding planes, rock faces encrusted with organisms, and ledges laden with sediment were photographed. A number of pictures interpreted as showing conglomerate were taken. Dredging from various places in this canyon had previously revealed conglomerate [*Shepard* and *Emery*, 1941].

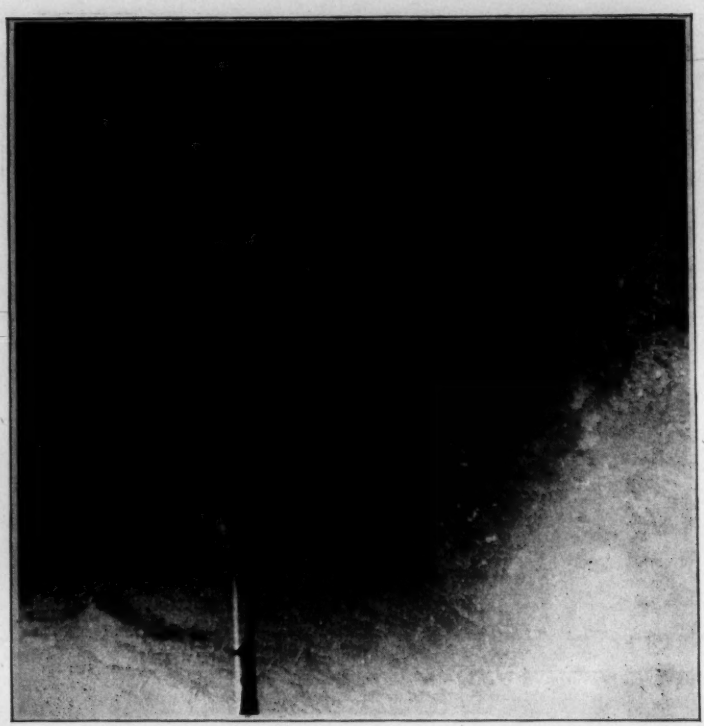

FIG. 4 – Jutting ledge at 300 ft on NW wall, Scripps Canyon; area of photograph unknown; photo data: f 10, $\frac{1}{10}$ sec, two #5 flash bulbs, Plus X film, camera to subject distance unknown

Extensive attempts were made to photograph terraces which might correlate with a Pleistocene lowering of sea level of 250 to 350 ft. No such terrace was found, although the wall between these depths was repeatedly photographed. Coverage, however, was not thorough enough to be certain that there are no terraces. The ledges shown in several photographs are much like the one in Figure 3, and seem hardly significant in this respect, being about 12 in wide. They probably represent nothing more than resistant beds of rock.

Heavy organic (animal) incrustation occurs at all depths photographed. No important changes in organisms seems to occur with increasing depth except the disappearance of the sea anemones. Fan and tube worms, starfish, and sponges and tunicates occur with greater frequency below 200 ft. In some photographs the fan worms almost cover the sheer rock faces with their extended arms (upper portion, Fig. 3).

Operations in 1952–53 with a longer frame resulted in 11 printable negatives from 25 lowerings. They included a much larger area of the canyon wall. A rock ledge photographed in August 1952 (Fig. 3) was rephotographed in August 1953 and found to have suffered no noticeable change in sediment veneer or organic growth. The 1953 picture has insufficient density to permit reproduction.

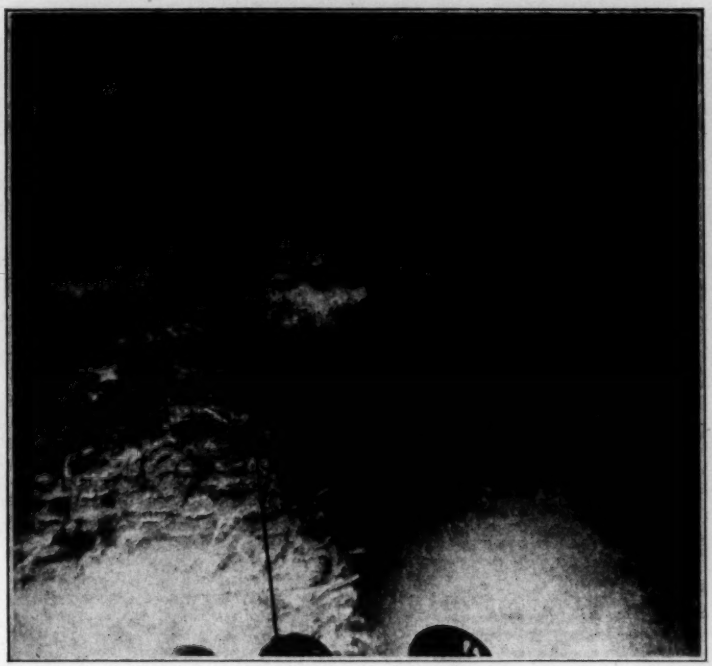

FIG. 5 – Angular re-entrant at 300 ft on NW wall, Scripps Canyon; area of photograph approximately 7.5 ft square; note thin bedded rock; photo data: f 5.6, $\frac{1}{100}$ sec, two #5 flash bulbs, Plus X film, camera to subject about 11.5 ft

Figure 4 very clearly shows a thin bedded rock ledge protruding from the canyon wall. This is one of several pictures illustrating ledges and angular irregularities along the course of the canyon. Figure 5 shows an angular re-entrant at a depth of 300 ft.

Conclusions—The equipment and methods herein presented should enable one to take photographs to a depth of more than 600 ft, and thus to delineate the features of near vertical walls of submarine canyons, and of fault scarps and reef faces, hitherto known only from dredging and sounding information. A more sturdy camera case should extend the depth range considerably. Man-made structures, such as bridge supports, dams, and piers, may be photographed using a modification of the equipment. Since the boat from which it is suspended is normally considerably ahead of the apparatus, it may not be used when the object to be examined extends above the surface. By suspending the unit from a boom and orienting it with cables extending laterally to the surface, one need only draw the far end slowly forward with another line, to obtain pictures of shallow structures.

The choice of frame size must depend upon the requirements of the survey, with long frames permitting examination of larger areas in each picture, and it is not unlikely that a close-up camera built along similar lines could be used to reveal

microstructure of sediments, and details of the organisms.

Acknowledgments—This project was supported by the Office of Naval Research under contract *N6-ori-111* (Task b). The DUKW was loaned to the project by the Beach Erosion Board, through D. L. Inman. Ted Anstead, the DUKW driver, saved the apparatus several times when it seemed irretrievably snagged deep in the submarine canyon. H. B. Stewart and M. A. Beal assisted with operations during 1952 and 1953 respectively. F. P. Shepard made the study possible by his support and encouragement, and this assistance is gratefully acknowledged.

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The Effects of Cable Design on the Accuracy of the GEK*

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Abstract—Simultaneous observations with a GEK and a drifting drogue were made in order to test the validity of the GEK for surface current measurements. The average current velocity was obtained by plotting the drogue trajectory by celestial fixes and other navigational means. Tests were conducted using various types of GEK cables. A cable having a density greater than that of sea water creates an error termed 'cable droop'; a lower cable density creates an error termed 'windage.' Good agreement between the average GEK velocity and the average drogue velocity is obtained when allowance is made for windage and droop.

The basic assumptions in GEK measurements—The method of towed electrodes, the Geomagnetic Electrokinetograph or GEK, as a technique for measuring ocean currents was first described by *von Arx* [1950]. Since then it has been widely used for surface current measurements in the open ocean, by *von Arx* [1952], *Bowden* [1953], *Murray* [1952], and others.

The theory of the GEK and the underlying assumptions involved in the interpretation of its results are best described by *Longuet-Higgins, Stern,* and *Stommel* [1954, referred to hereafter as *LSS*]. It is there shown that the potential E measured by the GEK is given by

$$\mathbf{E} = (\nabla\varphi - \mathbf{V}' \times \mathbf{H}) \cdot \mathbf{S} \tag{1}$$

where $\mathbf{V}'$ represents the velocity of the electrodes, $\mathbf{H}$ the Earth's magnetic field, and $\mathbf{S}$ the vector distance between electrodes. $\nabla\varphi$ is the potential gradient in the ocean and is given by

$$\nabla\varphi = \mathbf{V} \times \mathbf{H} - \rho\,\mathbf{i} \tag{2}$$

where $\mathbf{V}$ is the velocity of the water, ρ the electrical resistivity of the water, and $\mathbf{i}$ the electrical current density.

The velocity of the electrodes $\mathbf{V}'$ consists of three components: the course and speed of the ship, her leeway (if any), and the set and drift of the current itself. Hence,

$$\mathbf{V}' = \mathbf{V}'' + \mathbf{V}''' + \mathbf{V} \tag{3}$$

where the seconds and thirds refer to course and speed and leeway respectively. $\mathbf{V}'' + \mathbf{V}'''$ is the velocity of the ship relative to the water, which we will call $\mathbf{V}^*$. If there is any current shear, so that the current moving the electrodes is different from the current moving the ship, there must be one more velocity component in (3) to represent this difference. However, for most of the arguments that follow, the current difference component can be lumped with the windage component.

In making GEK measurements the electrodes are towed in two directions, x and y, (usually at right angles) and the two potential components are added vectorially: $\mathbf{E} = \mathbf{E}_x + \mathbf{E}_y$. If (1) is expanded (making the single assumption that $V'_z = 0$ where the z direction is normal to the surface of the water) then the potential measured when the ship is on the x leg is

$$E_x = \frac{\partial\varphi}{\partial x}S_x + \frac{\partial\varphi}{\partial y}S_y + \frac{\partial\varphi}{\partial z}S_z - V_y H_z S_z + (V_x + V^*_x)H_z S_y - (V_x + V^*_x)H_y S_z + V_y H_x S_z \tag{4}$$

(Although V'_x may not be zero at any instant, it most certainly has to be almost zero when averaged over a two to four-minute interval, the usual time for a GEK fix.) By the 'x leg' we mean that x is the direction of $\mathbf{V}^*$, not of $\mathbf{V}''$. A similar expression holds when the electrodes are towed on the y leg. In interpreting the potential measured by the GEK in terms of ocean currents the assumption is usually made that all terms but one in (4) are small and that to a good approximation

$$V_y \cong -E_x/H_z S_x \tag{5}$$

To go from (4) to (5) requires two assumptions

(a) $|\nabla\varphi| \ll |\mathbf{V} \times \mathbf{H}|$

(b) $S_y = S_z = 0$, that is, $\mathbf{V}^* \times \mathbf{S} = 0$.

The conditions which must be satisfied in the open ocean for the first assumption to be valid are discussed in detail by *LSS* [1954]. It is assumed in what follows, unless otherwise specified, that the first assumption is valid. The second assumption is related to the manner in which the electrode

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cable tows behind the ship and is the subject of this paper.

Cable droop—Until a few years ago nearly all GEK's in this country were equipped with Navy-type 'demolition cable' which has a diameter of approximately 0.35 inches and a specific gravity of about 1.8. This cable tows directly in the path the ship makes relative to the water (that is, $S_y = 0$ in (4)) but being denser than water it tows the far electrode at a greater depth than the near electrode (that is, $S_z \neq 0$). When this type of cable is used (4) becomes

$$E_x \cong -V_y H_z S_z - V^*{}_x H_y S_z - V_x H_y S_z \quad (6)$$

In practice the third term can usually be neglected. First, the current component V_x is usually much smaller than the ship velocity, $V^*{}_x$. Secondly, V_x is often cancelled because of the way in which GEK measurements are made. Since the electrodes tend to drift with respect to one another the usual practice is for the ship on at least one course to tow the electrode in first the x direction and then the $-x$ direction. The mean of the two observed potentials is used as the zero reference so that $\overline{E}_x$, the value used in determining V_y in (5), is simply

$$\overline{E}_x = E_x - \tfrac{1}{2}(E_x + E_{-x}) \quad (7)$$

In this manner any fixed potential between electrodes (as long as it remains constant over the period of measurement) is cancelled out. Thus the third term in (6) is cancelled. Both S_x and $V^*{}_x$ change sign as the ship changes direction, but V_x does not. Hence, when a cable with a density greater than that of sea water is used, the current component is related to the measured potential such that

$$V_y = \frac{-\overline{E}_x}{H_z S_z} - V^*{}_x \frac{H_y}{H_z} \tan \psi \quad (8)$$

where $\tan \psi = S_x/S_y$, where ψ is the angle the cable makes with the horizontal plane. By towing the electrodes at right angles and adding the components vectorially as in (3), it can be demonstrated that (8) becomes

$$\mathbf{V} = \mathbf{s}\frac{\overline{E}}{H_z S} + \mathbf{t}V^* \frac{H_h}{H_z} \tan \psi \quad (9)$$

where H_h is the horizontal component of the Earth's magnetic field, $\mathbf{t}$ is a unit vector pointing toward magnetic north, and $\mathbf{s}$ a unit vector pointing 90° to the left (to the right in the southern magnetic hemisphere) of the vector $\mathbf{V}$. (In practice, of course, towing the electrodes at right angles is almost impossible. However, the difference between 'ship's heading' and the actual path of the ship is usually not more than a few degrees and results in a relatively small error [see *LSS*, 1954].) It is assumed here that the magnitude of V^*, the speed of the ship through the water, is the same on both legs. This assumption may not be true when the sea is heavy or the wind strong.

If one neglects the S_z terms and calculates the current on the basis of (5), one arrives at (9) without the second term. Since this is the assumption that is usually made in GEK measurements, one can write (9) as

$$\mathbf{V} = \mathbf{V}_c + \mathbf{V}_f \quad (10)$$

where $\mathbf{V}$ is the 'actual current' assuming (6) is true, $\mathbf{V}_c$ is the current calculated in the usual manner from (5), and $\mathbf{V}_f$, which always points toward magnetic north, is the false signal caused by the fact that $S_z \neq 0$, and must be added to the calculated current in the usual way in order to arrive at the actual ocean current.

In order to know the magnitude of this false current it is necessary to know the value of $\tan \psi$. On four cruises in the past four years (Scripps Institution Cruises SHELLBACK, CAPRICORN, and EASTROPIC; and Pacific Oceanic Fishery Investigations Cruise 16 of the *Hugh M. Smith*) ships equipped with GEK's have made measurements at the magnetic equator (where H_z is zero) and in this way we have been able to measure the value of $\tan \psi$ for different ship speeds. The results are shown in Figure 1. The mean value of the direction of these 34 measurements was one degree east

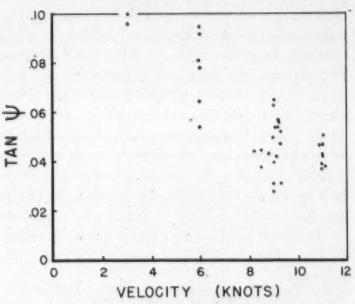

FIG. 1 – The angle a demolition cable makes with the surface when towed through the water at different speeds

TABLE 1 – *Representative values of the 'false current' caused by cable droop*

Area	H_s	H_h	V_f	Dir.
	oersted	oersted	cm/sec	°
Equatorial Countercurrent (Eastern Pacific)	0.18	0.33	40 ± 9	010
Kuroshio	0.32	0.31	21 ± 5	355
Florida Current	0.44	0.25	12 ± 3	360
California Current	0.43	0.25	13 ± 3	015
Gulf Stream	0.52	0.16	6 ± 1	345

from magnetic north with a standard deviation of three degrees. The mean standard deviation of $\tan\psi$ for ship speeds of 8.5 to 9.5 knots is $\tan\psi = (4.66 \pm 1.05) \times 10^{-2}$. In Table 1 are listed the values of $\mathbf{V}_f$ for a few representative areas assuming a ship's speed of nine knots.

In the area of the Gulf Stream and the Florida Current the assumption of $\nabla\varphi \cong 0$ is not in general valid, because the currents are still strong at depths which are not "small compared to the depth to the bottom" [*von Arx*, 1952; *Murray*, 1952]. The assumption of $S_z = 0$ results in a trivial error in the Gulf Stream (where the ratio of H_h/H_s is small and the currents are of the order of 50 to 250 cm/sec), and the error is still very small in the Florida Current where the currents are even stronger. It has been the experience of the authors in studying the California Current and the Equatorial Current system that the assumption $\nabla\varphi \cong 0$ is apparently valid. The droop correction on the other hand is large, amounting in both cases to a correction which is of the same order as the currents measured.

Neutrally buoyant cables—Over the past few years there have been several attempts to use cables which did not droop. This has been done by either floating the demolition cables or using neutrally buoyant cables. On the 1955 EASTROPIC Expedition to the Eastern Equatorial Pacific, neoprene cables (with a density about that of sea water) were used successfully. They were towed at the magnetic equator and showed no indication of droop. However, although $S_z = 0$ with this type of cable, it is not necessarily true that $\mathbf{V}^* \times \mathbf{S} = 0$. A cable which floats upon the water partly exposed to the air may be subject to transverse forces caused by the drag of the wind on the cable. In this case $S_y \neq 0$. Under these circumstances (4) becomes

$$E_x = -V_y S_z H_z + (V_z + V^*_z) H_z S_y \quad (11)$$

The sign of S_y does not change when the electrodes are towed in the opposite direction, and the equivalent equation to (8) in the case of wind-blown electrodes is

$$V_y = \frac{-\overline{E}}{H_z S_z} + V^*_z \tan\theta \quad (12)$$

where $\tan\theta = S_y/S_z$ and θ is the angle in the horizontal plane that the electrode cable makes with the path of the ship relative to the water. This angle is a function of the athwartship component of wind velocity. The equivalent of (10) is

$$\mathbf{V} = \mathbf{V}_c - \mathbf{V}_w \quad (13)$$

where the direction of $\mathbf{V}_w$ is approximately down wind. (If $\tan\theta$ is a simple linear function of the athwartship wind speed, then the direction of $\mathbf{V}_w$ is exactly down wind.)

For comparison we have, on two occasions, simultaneously towed both neutrally bouyant and demolition cables, the ship running in squares for a number of hours. The mean values of GEK measurements made simultaneously with neutrally buoyant cables $\overline{\mathbf{V}}_{nb}$ and demolition cables $\overline{\mathbf{V}}_d$, are shown in Figure 2. Values of $\overline{\mathbf{V}}_d$ have been corrected for droop. The vector differences given in Table 2 are defined by

$$\overline{\Delta\mathbf{V}} = \overline{\mathbf{V}}_d - \overline{\mathbf{V}}_{nb}, \quad (\overline{\Delta V^2})^{\frac{1}{2}} = [\overline{|(\mathbf{V}_d - \mathbf{V}_{nb})|^2}]^{\frac{1}{2}}$$

Directions are in conventional notation: currents are 'toward', wind is 'from.' On other occasions the two types of cable were towed together, but with only one recorder aboard ship it was necessary to record first one and then the other. In Figure 2 the difference in velocity of successive GEK's as measured by the two cables is plotted against wind direction. The magnitude of the individual vectors is the difference between successive measurements with first a neutrally buoyant cable and then a demolition cable; demolition cable values have been corrected for droop. The time between the two measurements is of the order of 20 min. The directions of the vectors in Figure 2 have been plotted against the observed wind direction, and the wind during the period of observation varied between 5 and 18 knots from 270° through 045°.

As can be seen from these tests the neutrally buoyant cable shows a consistent 'down-wind component' as predicted from (12). However, the interpretation of these data is somewhat ambiguous. The electrodes on the demolition cable tow at a depth of between 8 and 15 m. The electrodes of the neutrally buoyant cable are in the top meter. One might expect a wind-driven current superimposed upon the 'geostrophic current' to give a

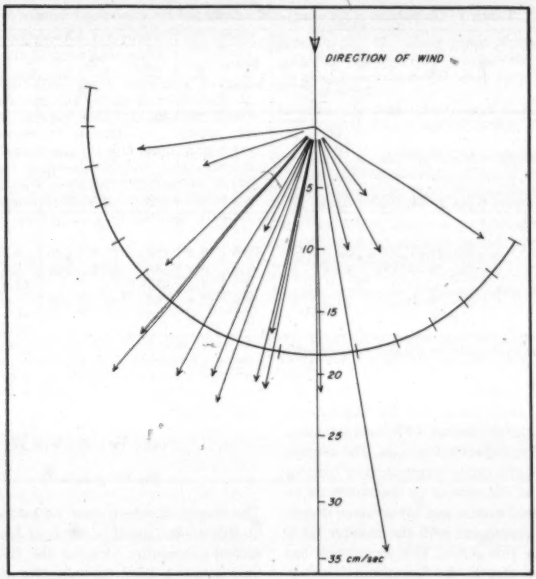

FIG. 2 – The difference in velocity as measured by a demolition cable and a neutrally buoyant cable

TABLE 2 – *Comparison with mean wind speed of the mean values of GEK measurements made simultaneously with neutrally buoyant cables* (V_{nb}) *and demolition cables* (V_d)

Date	Length of obs.	Number of observations	$\overline{V}_d$	Dir.	$\overline{V}_{nb}$	Dir.	$\overline{\Delta V}$	Dir.	Wind		$\overline{(\Delta V^2)}^{1/2}$
									speed	dir.	
	hr		cm/sec	°	cm/sec	°	cm/sec	°	cm/sec	°	cm/sec
July 26–27, 1955	22.5	43	8.9	339	2.6	283	7.4	171	9	285	16
Nov. 29–30, 1955	39.3	63	13.4	186	16.6	159	7.6	103	14	300	11

shear not unlike that observed, even though the interpretation of these GEK measurements as a measure of near-surface shear is rather complex [see *LSS*, 1954].

We have not yet been able to satisfy ourselves whether the observed difference is due to current shear, wind-blown electrodes, or both. There are two reasons for thinking the difference is not real, but caused by windage on the electrodes. One is discussed in the next section on tests of GEK validity. The other is essentially a negative argument. For the tests summarized in Table 2, the two cables were towed for a total of 106 observations. In addition there are the 30 successive measurements in Figure 2. In all of the 136 measurements the difference between the two cables was a vector which was always in the down-wind semicircle. The rms vector for the 106 cases where the measurements were made simultaneously is 13 cm/sec. (A simple calculation of the ratio of form to surface drag for a cable 10 to 50 pct exposed to air indicates that angles of this order (θ = 1 to 3°) might be expected.) More direct measurements of current shear [*Stommel*, 1954] indicate that although one might expect a down-wind component on the average, it would be unlikely that there always would be a down-wind component.

TABLE 3 – *Comparison of the mean GEK velocity with the mean drogue velocity*

Region	Date	Length of observations	Depth of drogue	Drift of drogue	$\bar{V}_g$	Dir.	$\bar{V}_t$	Dir.	$\bar{V}_g - \bar{V}_t$	Dir.	Maximum error in $\bar{V}_t$ area positioning
		hr.	m	mi	cm/sec	°	cm/sec	°	cm/sec	°	cm/sec
Equatorial Countercurrent	Oct. 30, 1955	11.5	5	8.2	38.0	081[a]	37	076	3	330	6.7
California Current (near Channel Islands)	Jan 21–24, 1952	65.3	20	7.3	4.3	060	5.7	070	1.6	277	0.8
	Jan. 24–27, 1952	69.0	10	25.8	15.1	187	19.3	179	4.8	335	0.8
	July 26–27, 1955	22.5	5	6.6	8.9	339	15.1	342	6.3	167	4.6
					2.6	383[a]			14.6	171	4.6
	Nov. 29–Dec 1, 1955	39.3	5	9.8	13.4	186	129	179	1.6	255	3.3
					16.6	159[a]			6.2	110	3.3

[a] Neutrally buoyant cable, no droop correction applied.

Tests of GEK validity—One way of testing the validity of the assumptions and the applied corrections is to make continuous GEK measurements around a free-floating surface drogue. The average velocity of the water can be ascertained by plotting the trajectory of the drogue by celestial fixes or other navigational means, and the average drogue velocity can be compared with the average GEK velocities during this period. This experiment has been performed once in the Equatorial Countercurrent with a neoprene 'neutrally buoyant' cable, twice in the California Current with demolition cable, and twice in the California Current with both demolition cable and neutrally buoyant cable. The results are shown in Table 3 in which $\bar{V}_g$ is the mean corrected GEK velocity and $\bar{V}_t$ the mean drogue velocity. In all cases the calculations were carried out under the assumption $\nabla\varphi = 0$. The false current due to cable droop was calculated from the data in Figure 1.

The agreement between mean GEK velocity and mean drogue velocity is good in most cases. The agreement between drogue and neutrally buoyant cable in the Countercurrent is excellent, and it is well within the possible error due to uncertainty of drogue positioning. This test was conducted in a calm sea. The two tests in which both demolition and neutrally buoyant cable were used show the drogue velocity in better agreement with the demolition cable than with the neutrally buoyant, which is another reason for thinking the down-wind component discussed in the last section is due to windage rather than current shear.

Summary and conclusions—The calculation of surface currents by (5) implies two important assumptions

$$(a)\ |\nabla\varphi| \ll |\mathbf{V} \times \mathbf{H}|$$

$$(b)\ \mathbf{V}^* \times \mathbf{S} = 0$$

The conditions which must be satisfied for (a) to be true are discussed in detail in *LSS* [1954]. The second assumption concerns the GEK cable and how it tows behind the ship. The use of a cable heavier than sea water results in the far electrode's towing deeper than the near electrode and introduces an error, which in the calculation of the current vector shows up as a 'false current' whose direction is toward magnetic north and whose magnitude increases as one approaches the magnetic equator. Measurements have been made of the cable droop for different ship speeds, the results of which are shown in Figure 1. Examples of the magnitude of the false vector are given in Table 1.

Tests with a neutrally buoyant cable towed in conjunction with a demolition (heavier than sea water) cable show that the difference in the two currents always results in a vector whose direction is 'down wind.' This current difference may be the result of shear, but it is more likely the result of the neutrally buoyant cable's making more leeway than the ship. This windage vector is of the order of 10 to 15 cm/sec and is independent of the magnetic latitude.

GEK measurements have been made around a drifting drogue and the mean value of the GEK observation compared with the mean velocity of

the drogue as indicated by the drogue trajectory. When proper corrections are applied for cable droop, the two are in good agreement.

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Utilizing the Decomposition of Organic Residues to Increase Infiltration Rates in Water Spreading

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Abstract—Decomposition rates were determined for several plant residues which were incubated under controlled conditions in the absence of soil. Three of these plant residues, having a range in decomposition rate from high to low, were mixed with soil, and incubated. The decomposition rates in the absence of soil were similar to those obtained when the plant residues were mixed with soil. Microbial counts made during the decomposition of the plant residues in soil showed that the greatest number of microorganisms occurred in the soils containing plant residues which decompose rapidly. Ammonium nitrate applied to the soil mixed with plant residue stimulated decomposition slightly. Percolation rates of soil mixed with organic residues varied with the amount of material applied, decomposition rate of the material, and the length of the incubation period. These studies indicate that initial decomposition at a moisture content near field capacity followed by decomposition at saturation may produce the highest infiltration rate for a given amount of organic residue. Infiltration rates on 0.005-acre test ponds containing vegetative cover or treated with cotton gin trash and alfalfa hay are presented. The use of organic residues to increase the infiltration rate of water-spreading areas is discussed.

Introduction—The favorable influence of organic residues on physical soil properties associated with high infiltration rates is largely due to the substances formed as a result of decomposition [*Martin*, 1942; *McCalla*, 1945]. It is necessary then to ascertain the decomposition characteristics of various organic residues and effects on infiltration rate in order to choose wisely among those locally available for use in increasing infiltration rates. The studies reported were carried out to determine the decomposition rates of various organic residues and to relate these results to management of water spreading areas for maximum efficiency.

'Water spreading' as used here refers to the practice of applying water to the surface soil and allowing it to infiltrate and percolate to the groundwater table. The purpose of water spreading may be the conservation of water by storage underground in aquifers or merely the disposal of excess surface water. In either case, high infiltration rates are desired in order to minimize the surface area set aside for this purpose.

Materials—For the decomposition studies the following materials were used: (1) cotton gin trash obtained from a local cotton gin; the gin trash had the following composition: cotton boll hulls, 66.5 pct; cotton stems, 10.0 pct; cotton seed, 2.4 pct; lint, 2.9 pct; cotton leaves, soil, and unidentified plant parts, 18.2 pct; (2) redwood sawdust obtained from an old, somewhat weathered sawdust pile; (3) alfalfa hay containing only a few leaves; and (4) Bermuda grass tops and roots obtained from a pure stand of sod; sod was removed to a depth of six inches when the tops were eight to ten inches high. The sod was washed free of soil, using a jet of water. Approximately 50 pct of the air-dry plant material consisted of roots. All materials were air-dried and ground to pass a two-mm sieve.

Decomposition of organic residues alone—In the first phase of this study, cotton gin trash, cotton stems, cotton boll hulls, cotton leaves, redwood sawdust, alfalfa hay, and a mixture of Bermuda grass tops and roots were selected for study. Air-dry portions of the organic residues equivalent to four grams of oven-dry material were weighed into 50-ml Erlenmeyer flasks. Distilled water was added to bring the moisture content up to 300 pct. The flasks were then plugged with cotton and incubated at 25°C for periods of 15, 30, 60, 120, 360, and 540 days. Moisture was replenished at weekly intervals by adding enough distilled water to bring the material back to 300 pct moisture. At the end of each decomposition period, duplicate flasks of each material were removed, oven-dried, weighed, and discarded. The loss in weight was calculated as per cent decomposition.

It is recognized that microbial decomposition, in the strict sense of the word, includes the degradation of the original organic residue with the formation of many intermediate products as well as gases and volatile liquids. Determination of these transformations was not within the scope of this study. Per cent decomposition as used herein refers to that portion of the original material which was lost as gas or volatile liquid as a result of microbial de-

composition. The portion remaining consists of organic materials, some of which have been shown to cause soil aggregation. This residue is subject to further microbial attack.

Results—Table 1 shows the cumulative decomposition of organic residues after various periods of time when decomposed alone. The most rapid rate of decomposition took place during the initial 15-day period. The portion remaining after each decomposition period is more and more resistant to microbial decomposition and, in consequence, the rate of decomposition declines. As material is assimilated by the microorganisms and tied up as microbial cells, the decomposition process may become limited due to a lack of nutrients such as nitrogen. The rate then becomes limited to the rate at which these nutrients are released when microbial cells die and decompose.

Decomposition of organic residues in soil—In order to compare the decomposition rate of organic residues in soil with that obtained when decomposed alone, alfalfa hay, cotton gin trash, and redwood sawdust were selected for further study. These organic residues had high, medium and low decomposition rates, respectively, when decomposed in the absence of soil. Hesperia sandy loam screened through a two-mm sieve was the soil used. This soil has an organic matter content of approximately one per cent and a field capacity of 13 pct moisture. The following treatments were applied to 50-gm samples of the soil: (1) no treatment; (2) one gm organic residue; (3) two gms organic residue; (4) two gms organic residue +0.0857 gms NH_4NO_3; and (5) 0.0857 gms NH_4NO_3.

The soil and organic residues were weighed into flasks and thoroughly mixed to obtain uniform distribution. The NH_4NO_3 was added in solution.

TABLE 1 – *Decomposition of organic residues incubated alone*

Organic residue	Days incubated						
	15	30	60	120	240	360	540
	Per cent decomposition[a]						
Cotton gin trash	24.0	33.0	41.6	50.1	56.4	58.1	62.2
Cotton stems	15.8	24.8	32.0	39.8	51.2	53.9	62.3
Cotton boll hulls	19.0	26.0	31.3	47.3	50.1	56.7	60.7
Cotton leaves	27.2	32.4	37.8	38.7	41.9	45.4	50.7
Bermuda grass tops and roots	29.8	36.9	45.3	48.1	51.2	54.6	55.2
Alfalfa hay	44.4	49.8	56.8	64.4	67.8	69.2	69.8
Redwood sawdust	2.1	2.3	2.4	3.3	9.6	10.2	14.3

[a] Per cent loss in weight of original material.

TABLE 2 – *Decomposition of organic residues incubated in soil*

Treatment	Days incubated			
	30	60	90	120
	Per cent decomposition[a]			
Gin trash 20 ton/ac	35.0	45.1	47.4	51.8
Gin trash 40 ton/ac	35.4	47.0	49.6	51.7
Gin trash 40 ton/ac + N	44.9	46.5	48.8	50.5
Alfalfa 20 ton/ac	43.2	47.8	48.9	52.8
Alfalfa 40 ton/ac	47.5	51.1	54.9	56.0
Alfalfa 40 ton/ac + N	54.8	55.9	56.4	57.5
Redwood sawdust 20 ton/ac	<0.5	<0.5	<0.5	1.4
Redwood sawdust 40 ton/ac	<0.5	0.8	2.3	3.5
Redwood sawdust 40 ton/ac + N	0.6	1.2	4.4	5.3

[a] Per cent loss in weight of original material.

Assuming that, in practice, the organic residue would be incorporated in the surface six inches of soil, which weighs approximately 2,000,000 lb per acre, one gm of organic residue in 50 gms of soil is equivalent to an application of 20 ton/ac. Distilled water was added to bring the soil moisture up to field capacity and an additional amount added equal to 300 pct by weight of the organic residue in order to supply enough moisture to wet the organic residue present. The flasks were plugged with cotton and incubated at 25°C for periods of 30, 60, 90, and 120 days. Moisture lost during incubation was replenished at weekly intervals. At the end of each period, three flasks from each treatment were removed. Two flasks were oven-dried and per cent decomposition determined from the loss in weight. The third flask was sampled for total microorganism counts, using sodium albuminate agar plates. The remainder of this soil was air-dried and reserved for laboratory percolation tests.

This air-dried soil was screened through a two-mm sieve and packed into small glass percolation tubes to form columns of soil 1.58 cm in diameter and ten cm long. The soil columns were then flooded continuously for a period of 28 days and the percolate measured daily. A ten-cm head of water was maintained on the soil columns by a small float valve serving all tubes.

Results—The results of the decomposition of these materials in soil are presented in Table 2. Slightly higher decomposition rates were obtained on all cotton gin trash treatments when decomposition occurred in soil instead of alone. Alfalfa hay mixed with soil at 20 and 40 ton/ac decomposed at a somewhat slower rate than when de-

composed in the absence of soil. With added nitrogen, the 40-ton/ac alfalfa treatment had a higher decomposition rate during the initial 30-day period than when decomposed without soil. For the remainder of the 120-day incubation, the rate of decomposition in soil was lower than when alfalfa decomposed alone. During the early part of the decomposition period, redwood sawdust showed less decomposition in soil than when decomposed alone. However, after 120 days incubation the 40-ton/ac treatments with and without added nitrogen showed slightly greater decomposition than the sawdust decomposed alone. From the above results, it appears that the decomposition rates obtained by decomposing organic residues alone can be used with reasonable accuracy to predict decomposition rates which would be obtained when organic residues are added to soil if moisture, aeration, and other conditions are favorable.

The addition of nitrogen to soil treated with organic residues increased the decomposition rate of all materials shown in Table 2 during early stages of decomposition. After 120 days no increase in decomposition was obtained on the gin trash treatment and only slight increases were still apparent in the alfalfa and sawdust treatments. The added nitrogen amounts to approximately 1.7 tons of nitrogen per acre.

Decomposition rates obtained on the 40-ton/ac treatments were slightly greater than on the 20-ton/ac treatments. This may be due to somewhat better aeration at the high application rate. It was observed that the 40-ton/ac soil and residue mixture appeared to have much more pore space than the 20-ton/ac treatment.

Plate counts of microorganisms made at the completion of each decomposition period are presented in Table 3. After 30 days, total numbers of microorganisms were greater in the 40-ton/ac treatments than in the 20-ton/ac applications of all residues. This condition persisted for the remainder of the 120-day period except on the 60- and 120-day samplings of the redwood sawdust treatment. When nitrogen was added, a decrease in total microorganisms was obtained at the end of the 30-day period on the alfalfa and cotton gin trash treatments compared with the same treatments without added nitrogen. Since the decomposition rates were increased by addition of nitrogen, the likely explanation for the decrease in microorganisms is that the period of most intense decomposition had passed and numbers of microorganisms had already decreased at the end of 30 days while numbers were still high in the samples receiving no nitrogen. The redwood sawdust treatment which received nitrogen showed an increase in total numbers over the same treatment which received no added nitrogen. At the low decomposition rate, the stimulating effect of the nitrogen was still apparent after 30 days. In treatments receiving added nitrogen, counts of total microorganisms tended to remain at a higher level than those not receiving nitrogen. Counts on soil without treatment and soil with added nitrogen were included for comparison. There was some increase in microorganisms when nitrogen was added to the untreated soil. The low decomposition rate of the redwood sawdust accounts for the relatively low numbers of total microorganisms recorded for this treatment.

The results of the laboratory percolation tests on the 40-ton/ac treatment incubated for 30 and 120 days are given in Figures 1 and 2. Percolation rate curves for the 20-ton/ac treatments are not presented since the curves are similar to those shown for the 40-ton/ac treatment, with the exception that the increase in percolation rate over untreated soil was not as large as with the greater organic residue application. The S-shaped curves are typical of those obtained in other tests conducted previously at this location [*Bliss* and *Johnson*, 1952].

The percolation rate obtained on soils treated with organic residues depends on the structure developed during the incubation and drying periods and subsequent clogging of soil pores during flooding. This includes aggregation, pore size, total pore space and continuity of pores. As flooding of the soil continues, the percolation-rate changes accord-

TABLE 3 – *Counts of total microorganisms in soil treated with organic residues*

Treatment	Days incubated			
	30	60	90	120
	Microorganisms per gram $\times 10^{-6}$			
Gin trash 20 ton/ac	140	70	58	65
Gin trash 40 ton/ac	373	119	138	132
Gin trash 40 ton/ac + N	354	173	217	181
Alfalfa 20 ton/ac	265	147	165	162
Alfalfa 40 ton/ac	301	223	332	266
Alfalfa 40 ton/ac + N	267	238	249	269
Redwood sawdust 20 ton/ac	14	12	13	12
Redwood sawdust 40 ton/ac	36	11	18	12
Redwood sawdust 40 ton/ac + N	49	13	24	17
Soil (no treatment)	11	14	14	3
Soil + N	19	17	14	14

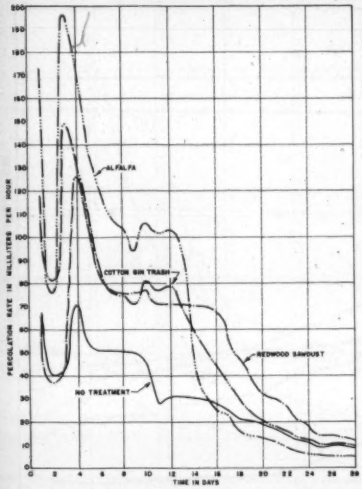

FIG. 1 – Percolation-rate curves of untreated soil and soil treated with organic residues at 40 ton/ac all incubated for 120 days and dried prior to test

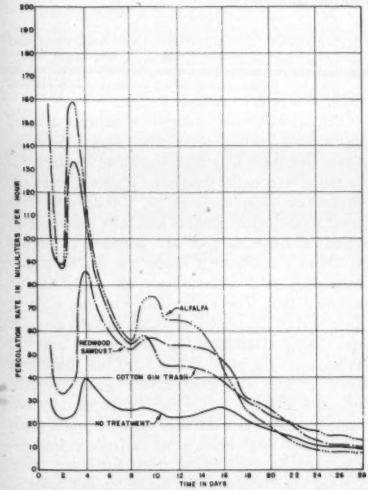

FIG. 2 – Percolation-rate curves of untreated soil and soil treated with organic residues at 40 ton/ac all incubated for 30 days and dried prior to test

ing to changes occurring in the factors affecting water movement, such as clogging by solid products of microbial activity, solution or accumulation of gases, or breakdown of soil structure either by the slaking or dispersing action of the water or by breakdown of binding substances by microbial activity. It is apparent from an inspection of Figures 1 and 2 that incubation of organic residues in soil for 30 or 120 days and drying prior to flooding increased the percolation rate over that of the untreated soil during most of the flooding period. However, at the end of 28 days, all treatments for both decomposition periods had reached approximately the same low rate. *Allison* [1947] presented data showing that the decrease in permeability of flooded soil occurring with time is due to microbial sealing at or near the soil surface. Assuming that microbial activity is the dominant factor producing clogging of soil pores and decline in percolation rate after the maximum is reached, then in order for the rates for all treatments to have reached the same low point after 28 days, the amount of microbial activity would have had to be greatest in the soil having the highest peak rate. The highest peak rate was obtained with alfalfa, followed in order by gin trash and redwood sawdust. This coincides with the decomposition rates obtained. It might be expected then that the rate of decrease in percolation obtained after the peak rate is reached on the curve would be greater with substances which tend to decompose rapidly than those which decompose more slowly so long as an appreciable decomposition rate was still going on at the end of the preflooding incubation. Inspection of Table 1 indicates that active decomposition was indeed still going on even after 120 days incubation. This decomposition would cause clogging of pores due to formation of gases or solids as decomposition products. However, the additional decomposition during the flooding period would provide additional stabilizing substances and result in increased structure improvement on drying previous to the next flooding period.

This is illustrated by the infiltration rates obtained on successive spreading runs on a small 0.005-acre field test pond (Figure 3). The curves were obtained over a six year period. A portion of this data was presented in a previous paper [*Bliss* and *Johnson*, 1952]. An additional spreading run has been made on the same pond and is included to further illustrate the increase in infiltration rates obtained. Curve 1 of Figure 3 shows the infiltration rate of the undisturbed soil prior to treatment. Curve 2 gives the results of the next test run made

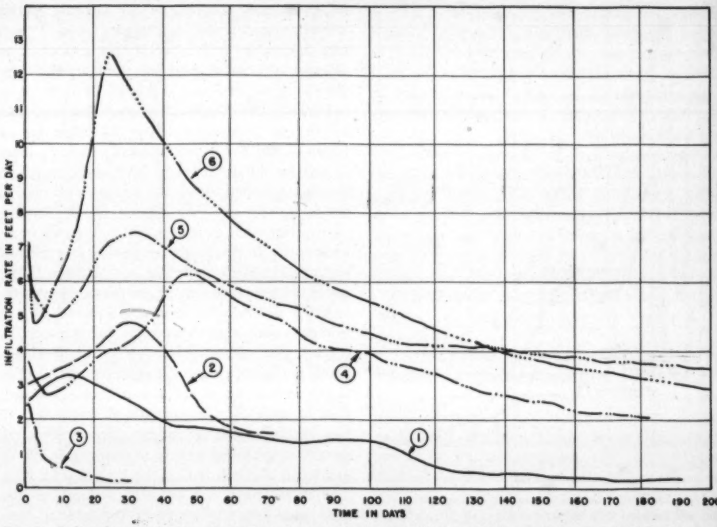

FIG. 3 – Infiltration rate curves of a test pond on successive spreading runs before and after application of organic residue treatments; see text for designation of curves

after 100 lb of manure and later a one-inch layer (five tons per acre) of alfalfa was spaded in and incubated by intermittent irrigation for several months. Some increase in infiltration rate was obtained. However, the rate soon declined to about the same rate as the untreated soil. The low infiltration rate obtained after spading in a six-inch layer of cotton gin trash and without a prior incubation or decomposition period is illustrated by Curve 3. The six-inch layer of gin trash, representing approximately 80 tons/ac, supplied large amounts of readily decomposable organic material. This material decomposing in the flooded soil produced large amounts of gases, slimes, and gums which clogged the soil pores and rapidly reduced the infiltration rate. In effect, Curve 3 represents an incubation period. After drying, the pond was again flooded, and a much improved infiltration rate was obtained as shown by Curve 4. This drying and reflooding was continued for two more cycles and improved infiltration rates obtained each time as presented in Curves 5 and 6. In each case improvement in soil characteristics associated with increased infiltration rates must have taken place during the previous flooding and drying period. Similar results have been obtained on other test ponds treated with gin trash. Untreated and undisturbed test ponds at this location declined in rates on successive runs.

The use of grasses to improve infiltration rates on water-spreading areas also shows promise. Grass sods have long been known to increase infiltration rates under conditions of natural rainfall. Infiltration rates obtained on a 0.005-acre test pond sodded with saltgrass and later reverting to volunteer Bermuda grass are presented in Figure 4. Curve 1 of Figure 4 shows the relatively low infiltration rates obtained on the newly-sodded saltgrass plot. The infiltration rate was slightly improved on the second run after the saltgrass sod was better established, as shown in Curve 2. Previous to the start of the third run, Bermuda grass became the predominant grass present. Curves 3, 4, 5, and 6 show the infiltration rates obtained on successive test runs after Bermuda grass became well established. Some variation in infiltration rates occurred among these latter test runs. Curves 3 and 6 have higher maximum and average rates for a 90-day period than Curves 4 and 5. The variation in maximum and average rates is

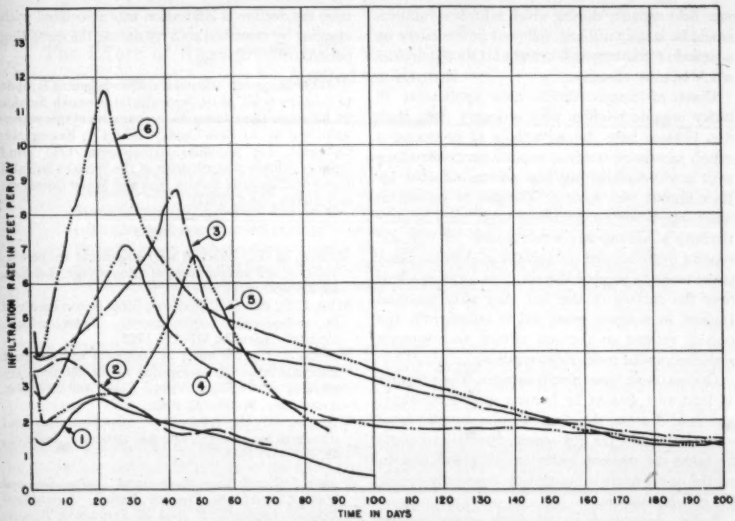

FIG. 4 – Infiltration rate curves of a test pond on successive spreading runs before and after a grass sod becomes established; see text for designation of curves

probably due to a variation in the organic residue produced as tops and roots during and after each previous run and the improvement in soil structure as a result of the decomposition of these residues as well as the stabilizing effect of the grass roots themselves. The amount of organic residue produced in this pond was not measured, and this factor needs further investigation.

Discussion—The shape of the infiltration-rate curve appears to be affected by the kind of organic residue incorporated in the soil and the length of the incubation or decomposition period as well as the rate of application. The choice of organic residue to use depends upon those locally available, their decomposition characteristics, and the length of time spreading is contemplated each year as infiltration rates decrease with time after a peak rate is reached. Organic residues which decompose rapidly may be most useful for temporarily increasing infiltration rates where short-term spreading for a few weeks is practiced. Where longer spreading periods are contemplated, a more slowly decomposing residue may be desirable so that the decline in infiltration rate after reaching a peak will not be as rapid. Gin trash falls into this category. This material produced high infiltration rates which held up well over an extended period of submergence in small test ponds. Materials such as redwood sawdust which decompose very slowly may not produce enough stabilizing substances at any one time to increase infiltration rates appreciably.

The moisture level maintained during the incubation or decomposition period could have a decided effect upon the infiltration rates obtained by treatment of soil with organic residues. Keeping the soil in a moist condition instead of saturated would minimize leaching of the soluble fraction of the fresh organic residue as compared to continuous flooding. When incubation is accomplished under continuous flooding, anaerobic conditions may develop; and relatively insoluble gases such as hydrogen and methane are produced. The gases apply a physical force within the soil pore space which tends to enlarge the pores. The solid products of decomposition stabilize this soil structure and, upon drying, further improvement in structure occurs. The result is a soil structure conducive to high infiltration rates. Perhaps a combination of initial incubation under moisture conditions at or

near field capacity during which soluble substances would be largely utilized, followed immediately by a period of continuous flooding and finally drying, would be most effective.

Costs of transportation and application of bulky organic residues may seriously limit their use. Grasses have the advantage of producing a supply of organic residues in place each year along with any beneficial physical effects afforded by their fibrous root system. The use of grasses or other vegetation on spreading areas may be particularly advantageous where waters of high silt content must be used for spreading. A dense plant cover tends to prevent the silt from forming a seal over the surface of the soil. Any silty material trapped in a dense grass sod is mixed with the organic residue on the soil surface and becomes stabilized as the residue decomposes.

Grasses have some disadvantages. They require at least two seasons to become well established; and in arid areas, they may require supplemental irrigation during the dry season. Special care must be taken to prevent reduction in stand due to partial or complete submergence, especially during the growing season.

Rapid decomposition of fresh grass residue during a flooding period could cause a corresponding rapid decline in infiltration rates. To avoid this possibility, it may be necessary to provide a period of wetting and drying prior to the time of proposed spreading operations each year. This would not only benefit soil structure but would tend to minimize the decline in infiltration rate associated with clogging by microbial activity during the spreading period.

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The Effect of Nonrepresentative Sampling on Linear Regressions as Applied to Runoff

W. D. POTTER

Abstract—Relations between peak rates of runoff and four rainfall and topographic indices are determined by linear multiple regressions for eight samples of gaged watersheds in the Allegheny-Cumberland Plateau. Three of these samples are representative and five are nonrepresentative as to watershed location and size. Precision of the eight regression equations in estimating peak rates of runoff is shown to be materially affected by the representativeness of the sample from which the equation was derived, decreasing rapidly as the degree of sample nonrepresentativeness is increased. It is concluded that the precision of such an equation as an estimator depends more on the representativeness of the sample than it does on the sample size.

Introduction—It is almost universal practice among research workers to draw samples in the form of measurements from a population about which it is desired to form conclusions or to make predictions. Too often, however, the research worker fails to recognize that he is using a sampling procedure and that the accuracy of his conclusions or predictions depends largely upon the adequacy of his sample. Many times this failure results in conclusions or predictions being made concerning a portion of the population that is either missing from the sample or is inadequately represented. This is particularly true of the hydrologist who attempts to explain the variations in peak rates of runoff within a homogeneous physiographic area by regression techniques. The effectiveness with which these techniques can explain the variations depends largely on how closely the sample of gaged watersheds represents the population from which it was drawn. A sample that includes only those watersheds located in one portion of a physiographic area may not be representative of the whole area. Likewise, a sample that is composed only of watersheds within a limited size range may not be representative of those watersheds falling outside of that range.

It is the objective of this study to determine the effect of such nonrepresentative sampling in either watershed location or size range on the reliability that may be expected from predictions based on regression equations derived from these samples.

Source of basic data—A brief description of the experimental data on which this study is based [*Potter*, 1953] and the procedures used in this paper follows:

In the Allegheny-Cumberland Plateau, an area considered to be homogeneous as to physiographic characteristics, all gaged streams draining areas up to 350,000 acres and having runoff records for the period 1938–1948 were screened to eliminate those where backwater conditions, diversions, or low-water control were found to exist. Instantaneous peak rates of runoff for an average frequency of once in ten years were computed from the streamflow records of each of the remaining 51 watersheds in accordance with the theory of extreme values [*Gumbel*, 1945; *Potter*, 1949]. The runoff records used for these computations were for the period 1938 to 1948. Two rainfall and two topographic indices were also computed for each of these watersheds. The logarithms of these values were used in a multiple linear regression in which the ten-year peak rates of runoff were considered as the dependent and the four indices as the independent variables. The resulting regression equation, hereinafter referred to as the original regression to distinguish it from those derived in this study, was as follows

$$\log q = -1.421 + 0.170 \log A - 0.554 \log T + 0.929 \log P + 0.449 \log S$$

in which

q = instantaneous peak rate of runoff that may be expected to be equaled or exceeded with a frequency of once in ten years, cfs per acre

A = area of watershed, acres

T = length of principal waterway in miles divided by the square root of the channel slope in feet per mile

P = rainfall intensity index derived from probability studies of maximum annual 60-minute rainfall intensities for the period of runoff record (1938–48)

S = rainfall frequency index derived from probability studies of the product of annual rainfall and the annual number of excessive storms for the period 1938–48

Table 1 is a tabulation of the 51 watersheds used

TABLE 1 – *Experimental data*

Watershed no.	Area	T	P	S	q
	1000 ac				
10c	0.122	0.041	0.99	1.90	0.830
5c	0.349	0.065	0.99	1.90	0.620
92c	0.920	0.142	0.99	1.90	0.400
43	1.05	0.220	1.00	1.30	0.229
94c	1.52	0.256	0.99	1.90	0.430
95c	2.57	0.399	0.99	1.90	0.360
97c	4.58	0.802	0.99	1.90	0.230
35	12.0	1.76	1.02	0.95	0.140
45	17.6	2.00	1.00	1.60	0.163
29	47.1	4.38	0.90	1.40	0.074
48	48.4	6.41	1.10	1.90	0.103
72	52.5	4.33	0.95	1.40	0.151
80	53.2	2.62	1.20	2.80	0.317
25	55.1	5.12	0.63	1.47	0.074
15	56.0	5.70	0.92	1.15	0.085
54	56.0	6.34	0.90	1.50	0.093
81	59.9	4.94	1.05	2.20	0.170
76	73.0	3.71	1.10	2.20	0.148
82	78.7	2.27	0.95	2.50	0.211
55	82.0	4.44	0.75	1.00	0.146
30	85.8	6.16	0.63	1.50	0.070
18	87.8	7.03	0.80	1.00	0.075
70	89.6	13.0	1.08	2.30	0.125
46	89.6	8.46	0.95	1.90	0.091
40	94.8	7.94	0.90	1.20	0.068
20	95.5	7.44	0.85	1.50	0.094
56	96.0	2.42	0.70	1.00	0.113
49	99.0	6.66	0.75	1.50	0.085
51	106.0	8.46	0.95	1.60	0.103
39	114.0	12.1	0.85	1.20	0.061
77	114.0	9.50	1.15	2.40	0.133
27	115.0	9.93	1.02	1.70	0.100
22	116.0	15.6	0.85	1.70	0.084
19	120.0	7.92	0.87	1.20	0.081
16	122.0	8.16	0.90	1.00	0.064
52	131.0	8.55	0.95	1.50	0.131
53	134.0	13.7	0.95	1.50	0.087
26	137.0	14.0	0.90	1.30	0.071
66	139.0	16.8	1.15	2.30	0.094
60	152.0	18.8	1.10	1.40	0.085
42	163.0	10.6	0.82	1.10	0.043
59	173.0	7.14	0.95	1.00	0.127
21	177.0	12.3	0.80	1.50	0.066
74	178.0	8.61	1.30	2.80	0.164
58	180.0	8.15	0.80	1.20	0.092
63	183.0	5.38	0.85	1.30	0.145
69	183.0	12.2	1.00	1.70	0.099
57	184.0	10.2	0.63	1.00	0.054
61	186.0	21.0	1.25	1.00	0.069
24	221.0	7.05	0.80	1.30	0.087
1	352.0	18.1	0.95	1.50	0.062
Green Lick Run	1.96	0.168	1.20	1.10	0.290
Muncy Creek	15.2	0.916	0.80	0.90	0.275
Big Piney Run	15.7	1.22	0.90	1.30	0.168

in the derivation of the original regression plus three additional watersheds (Green Lick Run, Muncy Creek, and Big Piney Run), together with the values of A, T, P, S, and q computed for each watershed. The data included in this tabulation comprise the experimental data used in this present study.

The population—In defining the population from which samples were to be drawn, it should be pointed out that this and similar studies [*Potter*, 1954] are aimed at providing the highway engineer with reliable estimates of peak rates of runoff for various frequencies that may be expected from ungaged watersheds. These estimates are needed by the engineers to assure the safe and economical design of highway bridges and culverts.

To be of maximum use to the highway engineer, the results of research studies must fulfill two basic requirements. (1) They must be presented in a form that is readily usable by engineers who may not have had extensive training in either hydrology or statistics. For this reason, regression equations are presented in the form of graphs or nomographs and rainfall indices are computed and shown on maps as lines of equal indices [*Potter*, 1954]. (2) Their application must be as extensive as possible without too great a sacrifice of accuracy. In other words, the smaller the number of graphs, nomographs, and maps that the engineer has to contend with, the greater the chances that he will make use of the research findings.

For the above reasons the population from which samples were desired was defined as the peak rates of runoff from all watersheds located in the Allegheny-Cumberland Plateau and having areas of from 1000 to 400,000 ac.

Measure of representativeness—To determine the extent to which a sample was representative with respect to the location of its constituent watersheds within the Allegheny-Cumberland Plateau, three location zones were selected. Zone 1 was defined as that portion of the Allegheny-Cumberland Plateau lying north of the 40th parallel (Fig. 1); Zone 2, that area between the 38th and 40th parallels; and Zone 3, that area south of the 38th parallel. Likewise, to determine the extent to which a sample was representative with respect to the distribution of its constituent watersheds within the designated size range (1000 to 400,000), three size groups were selected. Size Group A included watersheds with areas of from 1000 to 16,000 ac; Group B, watersheds with areas of from 16,000 to 100,000 ac; and Group C, watersheds

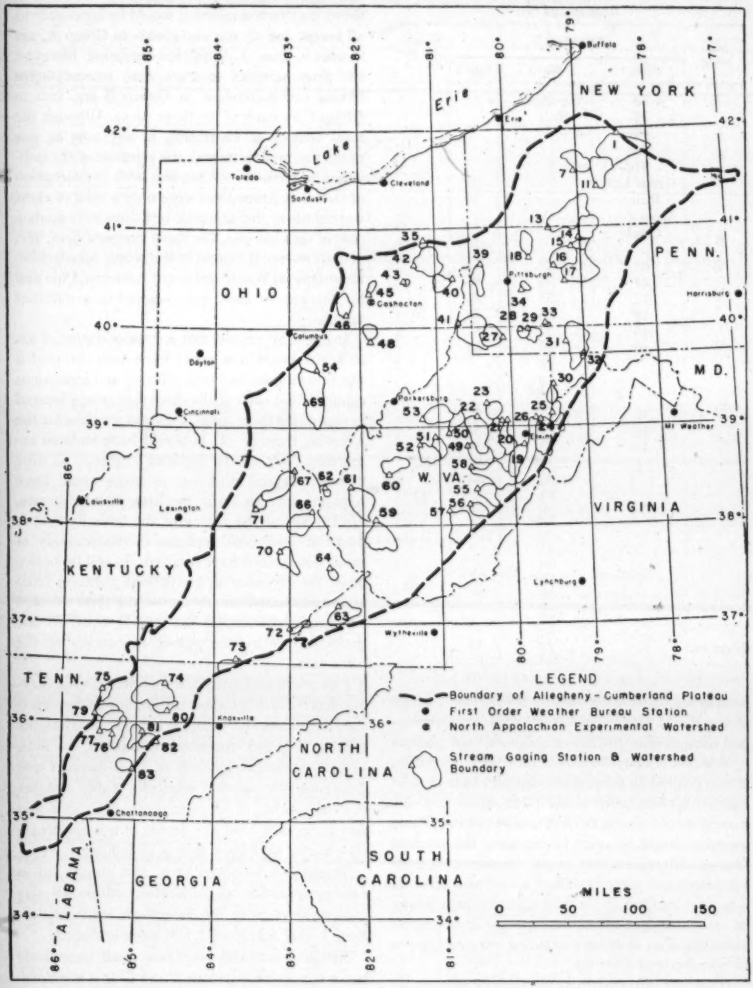

FIG. 1 – Allegheny-Cumberland Plateau

TABLE 2 – *Watersheds classified in accordance with location and size*

Size group	Watersheds in			Number of watersheds
	Zone 1	Zone 2	Zone 3	
A	43 35 94c 95c 97c Green Lick Run Muncy Creek	Big Piney Run		8
B	45 48 15 18 46 40	29 25 54 55 30 20 56 49	72 80 81 76 82 70	20
C	39 16 42 1	51 27 22 19 52 53 26 60 21 58 69 61 24	77 66 59 74 63 57	23
Number	17	22	12	51

with areas of from 100,000 to 400,000 ac. Table 2 shows the 51 watersheds used in this study classified according to the above zones and size groups.

Selection of samples—From the above tabulation it was desired to select three samples that were as nearly representative of all three zones and size groups as the available data would permit. These samples would be used to estimate the residual chance differences that might be expected from representative samples. They would also serve as a basis of comparison for differences in the accuracy of estimates that might be expected from regressions based on samples containing varying degrees of nonrepresentativeness.

It was decided that to be completely representative as to watershed size and location, a sample would have to contain an equal number of watersheds located in each of the three zones with the number in each zone distributed equally among the three size groups. An examination of Table 2, shows that such a selection would be impossible as all except one of the watersheds in Group A, are located in Zone 1. With this exception, however, the three samples selected were representative having two watersheds in Group B and two in Group C for each of the three zones. Although the total number of watersheds in any zone or size group was predetermined, the selection of the individual watersheds was random with the exception of Group A. Since there were only a total of eight watersheds in this group all but three were made a part of each sample. The three excepted (94c, 95c, and 97c) were all located in the North Appalachian Experimental Watershed near Coshocton, Ohio and for this reason each was assigned to a different sample.

It might be argued that a greater degree of accuracy of prediction would have been obtained if separate samples had been selected and regressions computed for each of the three size groups located in each of the three zones. This was not done for the following reasons: (1) It would have violated requirement (2) of the highway engineer, as nine nomographs and nine sets of maps would have been required to cover the area instead of one. (2) In view of the nature of the basic data, it is doubtful if any real increase in the accuracy of predictions would have resulted. As will be shown later, the accuracy of predictions obtained from regressions based on any one of the three selected representative samples was nearly equal to the limitation set by the probable accuracy of the basic data.

Five additional samples were selected with varying degrees of nonrepresentativeness as to watershed location or size group. Whenever the available number of gaged watersheds permitted, the individual watersheds for each of these samples was determined by random selection. Table 3 shows the composition of all eight samples by zone and size group. The kind and degree of nonrepresentativeness for samples 4 to 8 is as follows:

Sample 4 is balanced as to size groups but is nonrepresentative as to location within all size groups. Thirteen of the watersheds are located in Zone 1, only 5 in Zone 2, and none in Zone 3.

Sample 5 contains only two small watersheds but is balanced for Groups B and C. It is nonrepresentative as to location, having 17 watersheds in Zone 2, one in Zone 1, and none in Zone 3.

Sample 6 contains no Group A watersheds but is balanced for Groups B and C. It is nonrepre-

TABLE 3 – *Distribution of watersheds within samples by zones and size groups*

Size group	Sample no.																			
	Zone 1								Zone 2								Zone 3			
	1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
	Watershed designation[a]																							
A	43	43	43	43	35				BP	BP	BP	BP	BP											
	35	35	35	35																				
	94c	95c	97c	95c																				
	GL	GL	GL	GL																				
	MC	MC	MC	MC																				
B	40	45	18	40			45		30	55	30	49	29	56	30		70	82	72			72	72	
	45	48	40	48			48		29	20	54	29	25	54	56		72	76	81			80	80	
				15			15						54		20							81	81	
				46			18						55		49							76	76	
							46						30		29							82	82	
							40						20		25							70	70	
													56											
													49											
C	1	39	15	39				39	27	22	53	26	58	53		24	59	57	63			77		77
	42	16	16	16				16	26	26	58	58	19	51		19	77	59	77			66		66
				42				42					61			22						59		59
				1				1					22			58						74		74
													69			51						63		63
													26			69						57		57
													27			27								
													24			26								

[a] Abbreviations: GL = Green Lick Run; MC = Muncy Creek; BP = Big Piney Run.

sentative as to location, having 12 watersheds in Zone 3, four in Zone 2, and none in Zone 1.

Sample 7 is balanced as to location but nonrepresentative as to size, all 18 watersheds being in Group B.

Sample 8 has four watersheds in Zone 1, eight in Zone 2, and six in Zone 3. It is nonrepresentative as to size, all 18 watersheds being in Group C.

Multiple regressions—Using logarithms of values for the ten-year peak rates of runoff and the four independent variables A, T, P and S, (Table 1) a linear multiple regression was computed for each of the eight selected samples. The method of Gauss multipliers [*Goulden*, 1952, pp. 138–143] was used to determine partial regression coefficients. The regression equations were in the following form

$$\log \hat{Y} = \log a + b_{y1.234} \log X_1 + b_{y2.134} \log X_2 + b_{y3.124} \log X_3 + b_{y4.123} \log X_4$$

where,

$\hat{Y} = \hat{q}$ = estimated ten-year peak rate of runoff, cfs per acre

a = constant

$b_{y1.234}$, $b_{y2.134}$, $b_{y3.124}$, $b_{y4.123}$ = partial regression coefficients

$X_1 = A$ = area of watershed

$X_2 = T$ = length of principal stream divided by square root of slope

$X_3 = P$ = rainfall intensity index

$X_4 = S$ = rainfall frequency index

Table 4 shows values of log a and the regression coefficients for each of the eight regressions.

'Errors'—A new sample was selected with which to test the reliability of estimates made with the various regressions. With the exception of 94c and 97c, this test sample was arbitrarily made to consist of all of the watersheds contained in Samples 1, 2, and 3. The computed values of the independent

TABLE 4 – *Partial regression coefficients and constant log a*

Reg. no.	$b_{y1.234}$	$b_{y2.134}$	$b_{y3.124}$	$b_{y4.123}$	Log a
I	0.253	−0.639	0.790	0.554	−1.792
II	0.204	−0.581	0.045	0.347	−1.579
III	0.334	−0.696	0.630	0.519	−2.118
IV	0.137	−0.567	−0.279	0.455	−1.354
V	0.114	−0.403	0.619	0.065	−1.237
VI	0.096	−0.517	1.509	0.026	−0.948
VII	0.169	−0.515	0.919	0.558	−1.483
VIII	0.070	−0.708	0.621	0.628	−0.792

variables X_1, X_2, X_3, and X_4 for each of the 34 watersheds of the test sample were used in each of the eight regression equations to obtain values of $\hat{q}$, the estimated ten-year peak rate of runoff. Values of $\hat{q}$ were also obtained for the test sample from the original regression based on all 51 watersheds. These values were then compared with corresponding values of q, obtained from probability studies of the runoff record. The 'error' was taken as $\hat{q} - q$, and was expressed as a percentage of the estimated value $100(\hat{q} - q)/\hat{q}$. The average of the values of $\hat{q}$ obtained from regressions I, II, and III was also computed for each watershed of the test sample and used to obtain average errors.

The above errors for each regression were integrated for purposes of comparison by computing their distribution within the test sample. The absolute values of the errors were divided into groups. Starting with 0 to 5 per cent, the range of each succeeding group was increased by five per cent as, 0 to 10 per cent, 0 to 15 per cent, etc. For each regression, the number of watersheds for which the error was contained within the limits of each error group was tabulated and expressed as a percentage of the number of watersheds in the sample. This percentage was then plotted against the upper limit of each corresponding error group and an average curve drawn between the plotted points.

Comparison of error distribution for representative regressions—Since the sample of 34 watersheds was representative of all three zones and size groups and since the distribution of error curves were all derived for this same sample, they were used as a yardstick to measure the relative accuracy of prediction that might be expected from a general application of each of the regression equations. Before comparing distribution curves, derived from representative regressions with those derived from nonrepresentative regressions, however, it was desired to obtain an estimate of the difference in these curves that could be expected among regressions based on representative samples. If this difference were large, then observed differences between error-distribution curves based on representative and nonrepresentative regressions might be ascribed to chance rather than to nonrepresentativeness in the samples from which the regressions were derived.

To accomplish this, the error-distribution curve derived as the average curve for regressions I, II, and III (Fig. 2) was drawn among the plotted points (per cent sample versus per cent error) computed for each of the three individual representative regressions. An examination of these graphs showed a very close agreement between the average curve and the plotted points for the individual regressions. The average curve was an almost perfect fit for the plotted points derived from regressions I and III and differed by no more than two or three per cent from the error distribution curve for regression II. As a result of these comparisons it was concluded that the difference in accuracy that might be expected among representative regressions was small and that observed differences between the average error distribution curve and those derived from nonrepresentative regressions could be, therefore, ascribed to nonrepresentativeness rather than to chance.

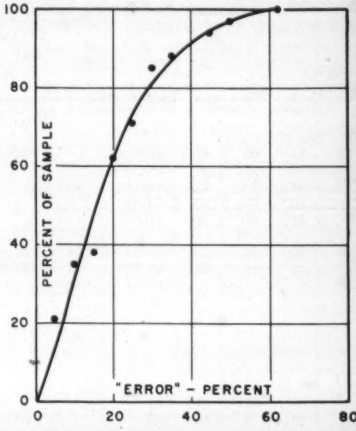

Fig. 2 – Distribution of error curve for average of regressionsI, II, and III

Comparisons of error distribution for representative and nonrepresentative regressions—Comparisons were now made between the average error-distribution curve for the representative regressions and those for each of the nonrepresentative regressions. With the exception of regression VII, the error for these regressions was greater than for the average representative regression. For regression VII, derived from intermediate Group B watersheds balanced as to location, the error-distribution curve was nearly identical to that for the average representative regression.

As further evidence that these increased errors

were due to sample nonrepresentativeness, watersheds that were in a size group or zone for which a regression was either wholly or partially nonrepresentative were successively deleted from the 34 watershed sample. A new distribution of error curve was then computed for the remaining watersheds. In all cases the errors for any per cent of sample were less after each deletion. The final curve was for those watersheds in size groups or zones for which the regression was representative and errors for these curves, in all cases, were less than for the average representative regression. The upper part of Table 5 summarizes the results of these deletions for 68 pct of sample size.

The above comparisons of accuracy of estimate were all for samples that contained varying proportions of watersheds that were in size groups or zones for which the regression was representative. For all of these the error decreased as the representative proportion of the sample was increased. Error-distribution curves were now computed for samples containing only watersheds in size groups or zones for which a regression was either partially or wholly nonrepresentative. These were compared with error-distribution curves computed for each of these samples from the average representative regression. The lower part of Table 5 summarizes these comparisons for 68 pct of sample size and illustrates the danger of extrapolating the relations established by a regression beyond the range of the experimental data. Errors for samples, in size groups or zones for which the regression was wholly nonrepresentative, varied among the nonrepresentative regressions from 31 pct for regression VII and 34 pct for regressions V and VI to 51 pct for regression IV and 57 pct for regression VIII. The variation in errors for the average representative regression for the same samples was only from 19 to 22 pct. It will be noted that errors increased rapidly with the degree of sample nonrepresentativeness.

Sample size versus sample representativeness—One other comparison of accuracy of estimate was made. The error distribution curve for the 34 watershed sample derived from the average representative regression (Fig. 2) was compared with that derived for the same sample from the original regression. As previously stated this latter regression was based on a sample of 51 watersheds. Although no attempt was made to control nonrepresentativeness in the selection of this sample, an examination of Tables 1 and 2 shows it to be nonrepresentative only to the extent that Samples 1, 2, and 3 are nonrepresentative; all watersheds

TABLE 5 – *Error in per cent q for 68 pct of sample size*

Watersheds of	Regression					
	IV	V	VI	VII	VIII	Average for I, II, & III
Entire sample[a]	32[b]	27[b]	26[b]	22[b]	31[b]	22[d]
Zone 3 deleted	26[b]					
Zone 2 & 3 deleted	19[d]					
Zone 1 & 3 deleted		15[d]				
Zone 1 deleted			17[b]			
Zone 1 & 2 deleted			13[d]			
Group A deleted				20[b]	26[b]	
Group A & C deleted				19[d]		
Group A & B deleted					18[d]	
Entire sample	32[b]	27[b]	26[b]	22[b]	31[b]	22[d]
Zone 1	19[d]	26[b]	34[c]			22[d]
Zone 2	33[b]	15[d]	20[b]			19[d]
Zone 3	51[c]	34[c]	13[d]			21[d]
Group A				31[c]	57[c]	22[d]
Group B				19[d]	31[c]	22[d]
Group C				21[c]	18[d]	20[d]

[a] Thirty-four watersheds.
[b] Partially nonrepresentative.
[c] Wholly nonrepresentative.
[d] Representative.

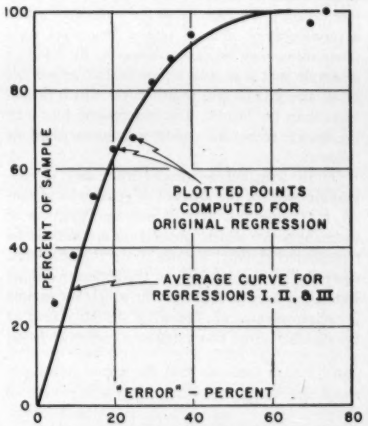

Fig. 3 – Comparison of distribution of error for original regression with average curve

except one in Group A being located in Zone 1. For this reason and because of the fact that it was based on a sample that contained nearly three times as many watersheds (18 versus 51), it might be expected that the accuracy of estimate obtained from the original regression would be better than that for the average representative regression. This, however, was not the case. When the distribution of error curve derived from the average representative regression was drawn among the plotted points of per cent of sample versus per cent error computed from the original regression, it was found to be an almost perfect fit for the plotted points (Fig. 3). From this comparison it may be concluded that the same general accuracy of prediction can be obtained from a regression based on a small sample as from one based on a sample three times that size, provided the extent of nonrepresentativeness in the two samples is approximately the same. In other words, the general accuracy of prediction depends not so much on the size of a sample as it does on the degree to which the sample is representative.

Discussion of results and conclusions—For the Allegheny-Cumberland Plateau, it has been shown that relations between peak rates of runoff and selected indices differ for different location zones and for different size groups.

It is seldom known at the beginning of a study of peak rates of runoff whether or not the relations that may be established are affected by watershed size ranges or by location of the watershed within a physiographic area. A safeguard against these possibilities may be taken, however, by selecting a sample that is as near representative as possible of all size groups and locations for which predictions may be desired. The conclusions that may be drawn from this study are summarized as follows:

(1) In selecting a sample from any physiographic area for the analysis of peak rates of runoff, it is important that all sizes and locations of watersheds for which predictions are desired be represented equally. Failure to do this may seriously reduce the accuracy of predictions for those watershed sizes or locations for which the sample is nonrepresentative. Likewise, statistics such as the standard error, computed for a regression based on such a nonrepresentative sample, should not be expected to apply to predictions for watershed locations or sizes not fully represented in the sample.

(2) Increasing the number of watersheds in a sample does not, *per se*, guarantee an increase in the accuracy of predictions. More important than the number of watersheds is the ability of the sample to equally represent all watershed sizes and locations for which predictions are desired. Thus a regression based on a small representative sample may be expected to have a greater accuracy of prediction than one based on a much larger nonrepresentative sample.

(3) Where a regression is based on a sample of watersheds located wholly in an intermediate zone or size group the reduction in the accuracy of prediction for watersheds in other zones or size groups is less than would have been the case had the sample been located wholly in an extreme zone or size group. For example, if no gaged watersheds in the smallest size group are available for some physiographic area, then predictions for this group will be more accurate if based on a sample of intermediate sized watersheds than if the sample contained only watersheds from the largest size group.

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Areal Representativeness of Point Rainfall

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Abstract—Shower-type rainfall data collected on several Illinois raingage networks, ranging in area from 19 ac to 400 sq mi, have been used to determine the areal representativeness of point rainfall measurements. Point rainfall was measured at the center of each area, and empirical relations for average and standard errors were developed for storm, weekly, and monthly periods. In addition, storm data for areas of 10 to 100 sq mi were used to obtain empirical relations between point and areal mean rainfall, when the point rainfall is measured by a gage displaced from the areal center by various distances. The results are considered representative of the Midwest and of other areas having similar climate and topography.

Introduction—The accuracy with which a point rainfall measurement represents the mean rainfall for areas of various size in the vicinity of the point observation is pertinent to the design of raingage networks for various purposes and in the interpretation of data from existing networks. Information regarding the relation between point rainfall and areal mean storm rainfall is especially applicable to hydrologic problems.

The lack of concentrated raingage networks for various sizes of areas which are necessary for deriving point-areal mean relations, has limited development of empirical relations in the past. Some limited data on the subject have been provided by *Linsley* and *Kohler* [1951] and the *U. S. Weather Bureau* [1947].

As a partial solution to the above problem, rainfall data collected on several concentrated networks in central Illinois during 1948–56 have been utilized to derive empirical relations between point and areal mean rainfall for various areas ranging from 0.03 sq mi (19 ac) to 400 sq mi. Point rainfall was measured at the center of each area and empirical equations developed for storm, weekly, and monthly periods. In addition, storm data for areas of 10 to 100 sq mi were used to obtain an empirical relation between point and areal mean rainfall when the point rainfall is measured by a gage displaced at various distances from the areal center.

Available data—Data used in this study were collected on the networks listed in Table 1. The two 100-sq mi networks were subdivided to obtain data for 10, 25, and 50 sq mi. The remaining data were obtained from separate networks. All networks were located in central Illinois on relatively flat terrain with no distinct topographic features to influence storm behavior. Distribution of gages on the networks was kept as uniform as the road systems and the availability of suitable exposures would permit. All gages were serviced by a technician. The various networks provided data for nine areal sizes from which a total of 1900 storm observations were available for derivation of empirical relations. The sampling scheme is illustrated in Figure 1, using one of the 100-sq mi networks.

All data used in the study were collected during spring, summer, and early fall; consequently, the developed relations are most applicable to shower-type rainfall. While the results are based on Illinois data, they should be approximately representative of the Midwest, and of other areas having similar climate and topography.

Average error—Various graphical plots were made for each areal size, relating point rainfall at the center to the difference between the point observation and the areal mean rainfall as measured by all gages within that particular area. Inspection of these graphical plots indicated that one of the following general expressions would fit the data best

$$\log E = k + l \log P \tag{1}$$

$$\log E = k + l P^m \tag{2}$$

In these expressions, P is the point rainfall for either the storm, weekly, or monthly observation at the center of a given area; E represents the difference between point and areal mean rainfall in the given area; and k, l, and m are regression constants. Values for k and l for storm, weekly, and monthly rainfall are shown in Table 2 for each network based on (1).

The values of l vary at random whereas the k-values show an increasing trend with area. Consequently, it was felt that the data from all networks could be combined into a single expression of the form:

$$\log E = k_1 + l_1 \log P + n \log A \tag{3}$$

TABLE 1 – *Raingage networks used in study*

Network area	Number of gages	Operational period
sq mi		
0.03	9	1953–56
0.6	5	1949–56
4	7	1950–55
10	9	1952–55
25	8	1948–54
25	12	1952–55
50	17	1948–54
50	28	1952–55
100	25	1948–54
100	48	1952–55
280	46	1948–50
400	50	1954–56

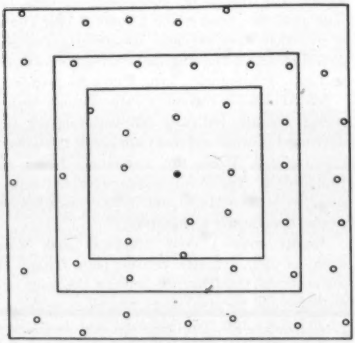

FIG. 1 – Areas of 25, 50, and 100 sq mi, Goose Creek, 1954

relating the measurement error of areal mean rainfall to the point rainfall P recorded at the center of the area and to the size of the area A. The constants k, l, and n were determined by the method of least squares, and the following empirical equations respectively for storm, weekly, and monthly rainfall were obtained

$$\log E = -1.431 + 0.50 \log P + 0.29 \log A \quad (4)$$

$$\log E = -1.285 + 0.58 \log P + 0.20 \log A \quad (5)$$

$$\log E = -1.559 + 0.71 \log P + 0.26 \log A \quad (6)$$

For comparison purposes, the data were next fitted to an expression of the form

$$\log E = k_2 + l_2 P^m + n_2 \log A \quad (7)$$

in which E, P, and A represent the same quantities as in (3), and k_2, l_2, m, and n_2 are again regression

TABLE 2 – *Regression constants for storm, weekly, and monthly equations on various areas*

Area	Storm		Weekly		Monthly	
	k	l	k	l	k	l
sq mi						
0.03	−2.155	0.46	−2.097	0.61	−2.301	0.72
0.60	−1.538	0.46	−1.469	0.61	−1.347	0.38
4	−1.377	0.47	−1.260	0.73	−1.252	0.86
10	−1.377	0.36	−1.229	0.62	−1.268	0.84
25	−1.222	0.52	−1.051	0.68	−1.252	0.78
50	−1.167	0.51	−1.060	0.78	−1.174	0.80
100	−1.131	0.50	−1.065	0.66	−1.131	0.74
280	−0.914	0.45	−0.783	0.69	...	...
400	−0.932	0.52	...	...	...	...

TABLE 3 – *Multiple correlation coefficients*

Equation	Correlation coefficient	Rainfall type
(4)	0.89	Storm
(8)	0.90	Storm
(5)	0.85	Weekly
(9)	0.85	Weekly
(6)	0.62	Monthly
(10)	0.60	Monthly

constants. The resulting empirical equations of best fit respectively for storm, weekly, and monthly rainfall from (7) are

$$\log E = -2.011 + 0.54 P^{0.5} + 0.29 \log A \quad (8)$$

$$\log E = -1.853 + 0.51 P^{0.5} + 0.18 \log A \quad (9)$$

$$\log E = -1.889 + 0.37 P^{0.5} + 0.25 \log A \quad (10)$$

Multiple correlation coefficients were then determined for (4), (5), (6), (8), (9), and (10) and are presented in Table 3. These correlation coefficients indicate there is no significant difference in the 'goodness of fit' provided by (3) and (7). However, graphical plots of the grouped data used in (4), (5), (8), and (9) indicated that (8) and (9) provide a somewhat better fit at high and low values of P. The smaller correlation coefficient obtained with the monthly data is due primarily to the fact that analysis was performed on ungrouped data, whereas the storm and weekly analyses were performed on grouped data. The number of individual monthly observations did not permit grouping. There were only 255 monthly values compared to 663 weekly totals and 1900 storm observations.

A comparison of the E values obtained for various P values from (4) and (8) for storm rainfall on an area of 100 sq mi is presented in Table 4. Only small differences in E are obtained from the

TABLE 4 – *Comparisons between (4) and (8)*

P	E for 100-sq mi area	
	Eq. (4)	Eq. (8)
inch	inch	inch
0.10	0.04	0.06
0.25	0.07	0.07
0.50	0.10	0.09
1.00	0.14	0.13
2.00	0.20	0.22
3.00	0.25	0.32
5.00	0.32	0.60

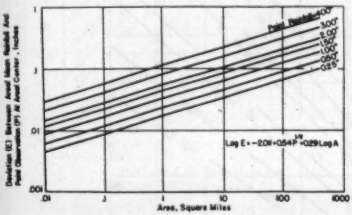

FIG. 2 – Storm relation between point and areal mean rainfall based on average deviations

two empirical equations below P values of three inches. Above three inches, (8) produces appreciably higher values of E than (4). As mentioned previously, indications are that empirical equations derived from (7) fit heavy rainfall data better. Since heavy rainfall is of prime interest to the hydrologist, further analytical efforts have been concentrated on this form of expression. Eq. (8) is represented graphically in Figure 2.

A comparison of E values obtained from the storm, weekly, and monthly equations is shown in Table 5. As expected, all three equations show that average difference E between point and areal mean rainfall increases as the storm size, represented by the point measurement at the areal center, increases. For a point rainfall measurement of a given magnitude, a trend exists for E to decrease with increasing sampling time as represented by storm, weekly, and monthly values. This trend becomes more pronounced as the rainfall at the areal center increases. It would appear therefore that a centered gage measures areal mean rainfall with an increasing degree of accuracy as the sampling period increases. Such a trend is to be expected. The weekly rainfall is usually the result of several storms and the monthly total normally contains more storms than the weekly total. In the absence of significant topographic or climatic

TABLE 5 – *Comparison between storm, weekly, and monthly relations*

Point rainfall	Average difference between point and mean rainfall for 100-sq mi area		
	Storm	Weekly	Monthly
inch	inch	inch	inch
0.25	0.07	0.06	0.06
1.00	0.13	0.10	0.10
2.00	0.22	0.17	0.14
4.00	0.45	0.34	0.22

features, the areal distribution of rainfall will tend to become more uniform as the number of storms increases, because individual storms tend to travel in various paths across a given area.

Confidence limits.—An estimate P of the areal mean rainfall becomes more meaningful when some measure is made of the possible error in the estimate. It is desirable to determine an interval about P with some measure of confidence that the areal mean does lie within that interval. To establish confidence limits, an estimate of the sampling standard error was required. This was made from 14 groups of storms having about the same P values. A standard deviation was computed for each of the following class intervals: 0.01–0.10, 0.11–0.20, 0.21–0.30, 0.31–0.40, 0.41–0.50, 0.51–0.60, 0.61–0.70, 0.71–0.80, 0.81–0.90, 0.91–1.00, 1.01–1.50, 1.51–2.00, 2.01–3.00, and 3.01–4.00. The regression constants were again determined for equations of the form represented by (7). The resulting equations respectively for storm and weekly rainfall are

$$\log s = -1.843 + 0.48\,P^{0.5} + 0.27 \log A \quad (11)$$

$$\log s = -1.731 + 0.46\,P^{0.5} + 0.19 \log A \quad (12)$$

In these equations, s (inches) represents the 'best' estimate of the standard error, P (inches) represents the midpoints of the class intervals, and A represents the area in square miles. Multiple correlation coefficients for (11) and (12) were 0.85 and 0.82, respectively. An insufficient number of monthly totals prevented the determination of a monthly standard error relationship.

The 95 pct confidence limits for storm and weekly areal mean rainfall were estimated by computing $P \pm 2\,s$ from (11) and (12). The resulting limits for storm rainfall are presented for several values of A in Figure 3. Other confidence limits may be determined if desired. For example, 70, 80, 90, and 99 pct confidence limits for storm and weekly areal mean rainfall may be estimated

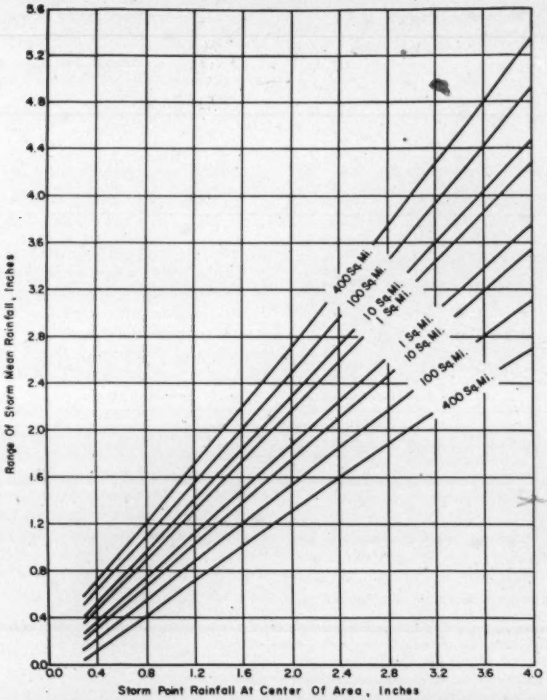

FIG. 3 – Ninety-five per cent confidence range for storm rainfall

by multiplying s in (11) and (12) by 1.05, 1.30, 1.67, and 2.66, respectively, and adding and subtracting from P.

Areal rainfall estimates from an off-center gage— Frequently, raingages are not located at or near the center of the area of interest. The nearest gage may even be outside the boundary of the area. It is logical to expect that a raingage which is located at a distance from the areal center will on the average give a less accurate estimate of the areal mean than a gage located at the center. The following paragraphs summarize an analysis to determine the accuracy of storm areal mean rainfall estimates from gages located at various distances from the center of several areas of different size.

Data from areas of 10, 25, 50, and 100 sq mi were analyzed. Analysis techniques were similar to those used in comparing areal mean rainfall with the rainfall amount obtained from a centrally located gage. An examination of the data indicated that an expression of the form

$$\log E = a + bP^c + d \log A + e \log D \quad (13)$$

followed the trend of the data satisfactorily. In this expression, E represents the average of the differences, A is the network area, D is distance from the areal center, P represents rainfall amount at the observation gage, and a, b, c, d, and e are regression constants. The equation obtained by fitting (13) to the data is

$$\log E = -1.411 + 0.51\, P^{0.5} - 0.01 \log A + 0.37 \log D \quad (14)$$

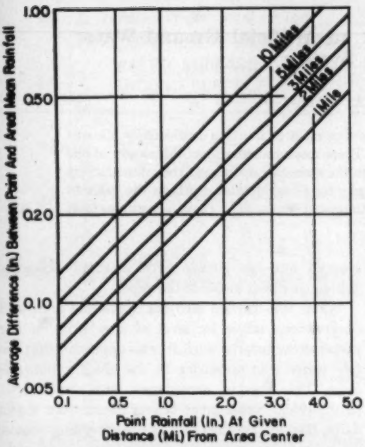

FIG. 4 – Effect of gage location on single gage estimates of mean rainfall on 100-sq mi area

In this equation E and P are in inches, A is in square miles, and D is in miles. The relation is illustrated for an area of 100 sq mi in Figure 4.

Within the limits of the data used, the magnitude of the coefficient of log A suggests that area is not an important variable. This result is rather difficult to rationalize. However, it may be because a gage located at any given distance from the center of two areas of different size is relatively closer to the center of the larger area. Consequently, the gage may be in an equally good position for sampling the mean rainfall in both areas. Since A contributes very little to the value of E and s in (14) and (15), the area variable could be omitted without significant error within the limits of area tested in this study.

An empirical equation for the standard deviation was determined for use in estimating confidence limits. This equation is

$$\log s = -1.179 + 0.41\,P^{0.5} - 0.01 \log A + 0.30 \log D \quad (15)$$

where s is in inches, and P, A, and D have the same definition and units of measurement as they had in (14). Confidence limits may be computed from (15) for various combinations of P, A, and D as was done in the section on confidence limits.

Summary—The approximate magnitude of the measurement error when a point rainfall value is assumed to represent the mean rainfall in surrounding areas of various size was determined. Analysis has been concentrated on warm season (shower-type) precipitation when the areal rainfall variability is relatively large, and consequently, when the areal representativeness of a point rainfall measurement is most doubtful. The data were subjected to various statistical analyses to determine empirical equations of best fit. Studies were performed on storm, weekly and monthly data to ascertain the effect of storm integration and length of observational period on the measurement error. Investigation was also made of point rainfall representativeness when the observation point is displaced at various distances from the center of the area of interest. To define better, the reliability of areal mean rainfall estimates based upon point rainfall observations, both average and standard errors of measurement were determined, and 95 pct confidence bands established.

Throughout the study, efforts have been made to analyze from the standpoint of practicality. It is hoped that the results will prove useful to hydrologists, meteorologists, and others interested in establishing raingage networks and interpreting data collected from existing networks. The results should also be valuable to those interested in evaluating and utilizing radar for quantitative precipitation measurements.

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Perched Water Tables under an Artificial Ground-Water Recharge System

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Abstract—Hydrostatic pressure measurements were made at fourteen depths below the surface of a large ground-water recharge system. These measurements show the nature of the growth of the perched water tables resulting from the spreading operation. They demonstrate the importance of knowing subsurface stratigraphy for a considerable depth on the value to be derived from treatment of the surface soil to improve permeability. These factors also limit the potential capacity of a recharge area.

Introduction—Artificial ground-water recharge by the use of spreading basins has been practiced in the southern San Joaquin Valley for many years. At present the Kern County Land Co. has set aside over 1100 acres of otherwise productive land for water-spreading ponds. Two basic factors are recognized as limiting the amount of water which can be returned to ground water by this method. The first is the decline in surface permeability caused by microorganisms [*Allison*, 1947] and by swelling of the colloidal fraction of the soil upon wetting. This phase of the problem has been discussed by *Schiff* [1955], *Bliss* and *Johnson* [1952] and in reports of the Kern County Land Co. on water-spreading activities from 1936 to present.

The second factor limiting the infiltration rate during prolonged submergence is the subsurface stratigraphy. To explore the effects of variations in permeability with depth, a large spreading area was instrumented with piezometers and observations were taken during the subsequent spreading season.

Instrumentation—The piezometers were one-half inch pipes jetted into position with a large spray rig using a method similar to that reported by *Reger* and others [1950]. The central nest consisted of piezometers to depths of 1, 2, 3, 4, 5, 7½, 10, 12½, 15, 17½, 20, 30, 50, and 80 ft below the bottom of the spreading pond. A log was kept on the type of material washed up by each jetting operation. Close agreement as to type, location and thickness of strata was noted for all holes in the same nest. Some differences were noted between the four outer nests (placed from 100 to 300 ft away from the central nest) but continuity of the principal less-permeable strata was observed.

After jetting, the hole around each piezometer was carefully sealed by flowing a slurry of mud into the space, working the pipe to settle it in position. After sealing, the inside of each piezometer was cleaned out by jetting with a small diameter tubing let down inside of the pipe.

Water was turned into the spreading area and observations made for level of free water in the piezometers hourly until it was apparent that no free water was appearing in the shallow piezometers. This was in accordance with predictions [*Hall*, 1955]. Subsequent observations were made daily, then every other day as the spreading season progressed.

Results—The results are given in Figure 1 in which is plotted the total hydraulic head above an arbitrary datum as a function of the depth of the bottom of the piezometers below ground surface. Thus, points lying above the 45° line represent positive or excess hydrostatic pressure. Points below this line represent tension [*Day* and *Luthin*, 1953]. Since tension was not observed in this study it was not possible to plot a complete hydraulic grade line.

Data points are indicated by appropriate symbols in the figure. For clarity some intervening points representing observation on successive days are omitted although they firmly support the pattern shown. Some liberty was taken in constructing the estimated position of the hydraulic grade line. Here use was made of the knowledge of stratigraphy to estimate the slope and termination of the line in each strata.

These data show several interesting features. First the pressure head between the surface and the less permeable subsurface strata develops in a manner analogous to the filling of a jug, that is, from the bottom up rather than from the surface downward by the advance of a saturation front. Although the water surface in the pond was kept at approximately 1½ ft above the ground surface, water did not show in the piezometer one foot below the ground surface until it was backed up from below by the clay layer at a depth of 20 ft.

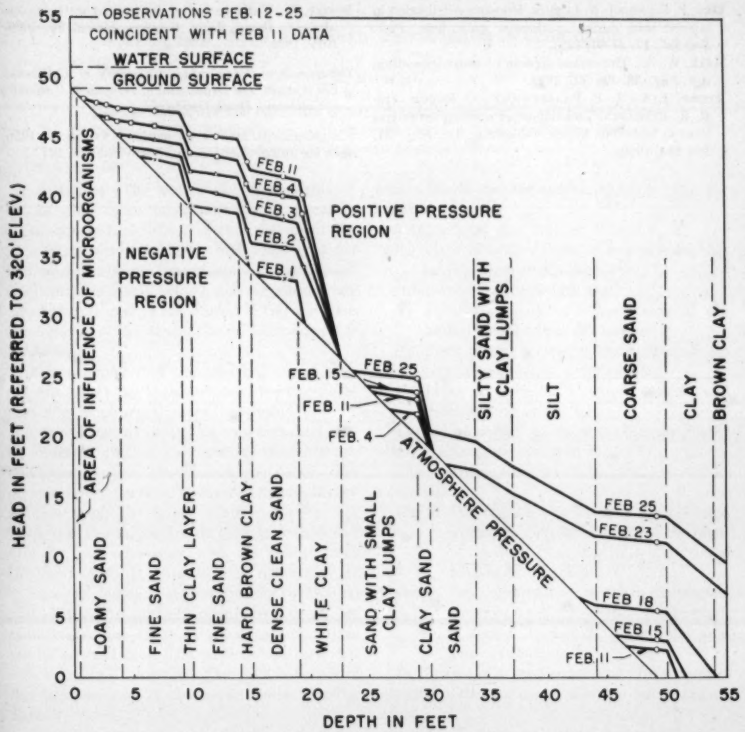

FIG. 1 – Hydrostatic pressure conditions in a stratified soil beneath a large water-spreading area

At this location, as at others similarly instrumented, the merging of the perched water table with surface water resulted in a sudden decrease in infiltration rate.

Surface treatment could improve the infiltration rate of these ponds for a period not to exceed about 30 days. After this, the adverse effects of subsurface conditions would far overshadow the beneficial effects of surface treatment. Improved initial rates would tend to fill the soil sooner but during the entire spreading season would not materially increase the total quantity of recharge of a large water-spreading area.

This study emphasizes the need for careful subsurface exploration in designing a ground-water recharge system if subsurface conditions are not to be permitted to control infiltration rates. Water spreading sites cannot be selected by the nature of the surface soil alone if large quantities of water must be returned to underground storage.

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Pacific and 'Mediterranean' Earthquake Mechanisms

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Abstract—Similarities and differences between the earthquake mechanisms of the Circum-Pacific Belt and the 'Mediterranean' zone are considered and tentative conclusions are drawn about the underlying causes of earthquake generating stress systems.

Introduction—The earthquake mechanisms of shocks with a magnitude greater than, or equal to, 6 are arranged according to the position of the principal stress components with respect to the vertical. Data on the type of faulting are compiled from the references below, the magnitudes are taken from *Gutenberg* and *Richter* [1954] and from the *Bulletins of the Bureau Central International de Séismologie.*

It is assumed that the principal stress components bisect the angles between the two nodal planes for longitudinal waves in the focus.

It is realized that according to the method used by different authors the resulting data are not homogeneous [see also *Scheidegger*, 1955]. The greater part of the data, however, is determined by authors using the more reliable methods (see Table 1). The earlier Dutch work is revised and brought into accordance with the newest ideas [*Ritsema*, 1956]. It is possible to argue over 32 solutions of Japanese authors (mainly by Honda) and 12 of Soviet authors (mainly by Kogan) [see also *Scheidegger*, 1955]. It seems, however, that the influence of these data on the whole picture is only of minor importance. Therefore the work of the Japanese and of the Soviets is included in Table 1.

Classification of earthquake generating stress systems—Three main types of earthquake mechanisms can be distinguished:

V_t Plane of action more or less vertical, dip tension smaller than dip pressure (normal fault movement). (The plane in which the fault movement takes place and in which the principal stress components are acting is called the plane of action. This plane stands perpendicular to the fault plane.)

V_p Plane of action more or less vertical, dip pressure smaller than dip tension (reversed fault movement).

H Plane of action more or less horizontal, tension and pressure both more or less horizontal (transcurrent fault movement).

In the case of a random position of the plane of action the chances for each of the three types are equal.

A transitional case between V_t and V_p is:

V_- Plane of action more or less vertical, dip tension equal to dip pressure.

Subdivisions of the H type are:

H_t Plane of action more or less horizontal, dip tension smaller than dip pressure.

H_p Plane of action more or less horizontal, dip pressure smaller than dip tension.

H_- Plane of action horizontal, tension and pressure both horizontal.

Typical examples of each of the mentioned stress positions are shown in Figure 1.

The following division of earthquakes can be made also:

T shocks Dip tension smaller than dip pressure, irrespective of the position of the plane of action (V_t and H_t) (horizontal tension earthquakes).

P shocks Dip pressure is smaller than dip tension, irrespective of the position of the plane of action (V_p and H_p) (horizontal pressure earthquakes).

In the case of a random position of the plane of action the chances for each of the two types are equal.

Data—All shocks mentioned in the introduction were reconsidered and the position of the plane of action in each case was determined. In total there are 149 earthquakes (see Table 1).

Shocks of a magnitude smaller than 6 have not been used in this study to prevent a too inhomogeneous distribution of data throughout the seismic zones of the Earth. Most of the smaller shocks were aftershocks of some heavy earthquake and therefore are concentrated in restricted regions.

A division is made between Pacific and 'Mediterranean' shocks, with epicenters in the Circum-Pacific Belt and the Mediterranean-Trans-Asiatic Belt respectively. Therefore the earthquakes of the Indonesian and Philippines archipelago have been included in the 'Mediterranean' group, those of

TABLE 1 – *List of earthquakes studied*

No.	Date	GMT	Epicenter: Region no[a]	Epicenter: Seismic belt	Depth	M	Type	Ref
1	3/7/27	09h28m	19	Pac.	0.00 R	7½	V_p	H
2	11/25/30	19 03	19	Pac.	0.00 R	7.1	H_-	M
3	1/9/31	01 46	19	Pac.	0.02 R	6	V_p	K
4	2/20/31	05 34	46	Pac.	0.05 R	7.4	H_-	M
5	4/21/31	00 02	19	Pac.	0.05 R	6	H_-	M
6	6/2/31	02 28	19	Pac.	0.03 R	6½	H_-	M
7	6/29/31	16 43	19	Pac.	0.05 R	6½	H_p	M
8	9/21/31	02 20	19	Pac.	0.00 R	6½	H_-	M
9	9/25/31	06 00	24	Med.	0.00 R	6	V_p	V
10	11/2/31	10 03	20	Pac.	0.00 R	7.5	H_-	M
11	4/4/32	19 17	18	Pac.	0.06 R	6½	V_-	M
12	7/25/32	08 25	19	Pac.	0.05 R	6½	V_t	M
13	9/23/32	14 23	46	Pac.	0.05 R	6.9	V_-	M
14	11/26/32	04 24	19	Pac.	0.00 R	6½	H_-	M
15	3/11/33	19 33	18	Pac.	0.07 R	6½	V_t	M
16	5/16/33	01 12	24	Med.	0.00 R	6½	V_p	V
17	6/24/33	21 55	24	Med.	0.00 R	7.5	V_p	V
18	9/2/33	16 42	18	Pac.	0.05 R	6½	V_t	M
19	9/21/33	03 14	19	Pac.	0.00 R	6½	H_-	M
20	12/4/33	19 34	46	Pac.	0.05 R	6½	V_-	M
21	5/1/34	07 05	24	Med.	0.02 R	7.0	V_p	V
22	6/29/34	08 25	24	Med.	0.11 R	6.9	V_t	R
23	7/6/34	22 49	3	Pac.	0.00 R	6.5	H_p	B
24	4/15/35	11 15	19	Pac.	0.04 R	6½	H_t	M
25	5/31/35	08 19	19	Pac.	0.07 R	6½	H_t	M
26	8/3/35	01 10	24	Med.	0.00 R	7.0	H_t	V
27	11/25/35	10 03	24	Med.	0.00 R	6½	V_t	V
28	12/28/35	02 35	24	Med.	0.00 R	7.9	V_p	V
29	5/8/36	09 12	24	Med.	0.09 R	6½	V_t	R
30	6/25/36	16 52	18	Pac.	0.05 R	6½	V_-	M
31	8/23/36	21 12	24	Med.	0.00 R	7.3	H_p	V
32	10/26/36	09 34	19	Pac.	0.05 R	6½	V_-	M
33	12/1/36	06 10	20	Pac.	0.04 R	6½	V_-	M
34	4/29/37	20 20	46	Pac.	0.05 R	6½	H_-	M
35	7/1/37	11 50	24	Med.	0.01 R	7	V_p	V
36	7/22/37	17 09	1	Pac.	0.00 R	7.3	H_t	A
37	8/11/37	00 52	24	Med.	0.09 R	7.2	V_t	R
38	1/11/38	15 12	20	Pac.	0.00 R	6½	H_-	M
39	2/7/38	14 43	19	Pac.	0.01 R	6½	H_-	M
40	5/28/38	16 42	19	Pac.	0.00 R	6½	H_-	M
41	7/29/38	13 07	24	Med.	0.01 R	6½	H_p	V
42	8/18/38	09 30	24	Med.	0.01 R	6.9	V_p	R
43	8/25/38	01 28	24	Med.	0.01 R	6.9	V_t	V
44	10/20/38	02 19	24	Med.	0.01 R	7.3	V_t	R
45	11/15/38	21 00	24	Med.	0.00 R	6½	H_-	V
46	4/21/39	04 30	46	Pac.	0.08 R	7.0	V_t	M
47	6/18/40	13 53	22	Med.	0.08 R	6½	V_t	R
48	9/22/40	22 52	22	Med.	0.10 R	6½	V_t	R
49	1/31/41	02 39	24	Med.	0.03 R	6½	V_t	R
50	3/16/41	16 35	31	Med.	0.01 R	6½	H_-	D
51	7/15/41	14 45	19	Pac.	0.00 R	6	H_-	M
52	9/17/41	06 48	23	Med.	0.03 R	7.1	H_t	R
53	4/20/42	08 41	19	Pac.	0.05 R	6½	V_-	M
54	6/8/43	20 43	24	Med.	0.00 R	7.4	V_p	V
55	6/9/43	03 06	24	Med.	0.00 R	7.6	V_p	V
56	7/23/43	14 53	24	Med.	0.01 R	7½	V_p	V
57	9/10/43	08 37	20	Pac.	0.00 R	7.4	H_-	M
58	10/13/43	05 42	19	Pac.	0.00 R	6	H_-	M
59	11/17/43	14 58	18	Pac.	0.05 R	7.0	V_-	M
60	11/26/43	21 25	24	Med.	0.02 R	7.1	V_p	V
61	1/5/44	21 13	24	Med.	0.00 R	7.0	V_p	V
62	3/26/46	17 09	24	Med.	0.00 R	6½	H_-	V
63	5/8/46	05 20	24	Med.	0.00 R	7.1	V_p	V
64	10/16/47	02 09	1	Pac.	0.00 R	7½	V_t	H
65	6/28/48	07 13	19	Pac.	0.00 R	7½	H_-	M
66	6/29/48	10 29	12	Pac.	0.01 R	7	H_p	W
67	9/8/48	15 09	12	Pac.	0.00 R	8	V_p	W
68	12/15/48	19 12	18	Pac.	0.03 R	6½	V_t	K
69	12/30/48	23 50	2	Pac.	0.00 R	7	V_t	H
70	4/5/49	09 27	46	Pac.	0.08 R	7½	H_p	H
71	4/13/49	19 56	2	Pac.	0.00 R	6½	V_p	H
72	4/20/49	03 29	8	Pac.	0.01 R	7½	H_-	H
73	5/3/49	05 57	19	Pac.	0.01 R	7	H_p	H
74	5/21/49	21 40	18	Pac.	0.00 R	6½	V_p	K
75	6/12/49	17 52	8	Pac.	0.09 R	7.0	H_-	H
76	7/23/49	10 26	14	Pac.	0.03 R	6½	H_p	H
77	8/5/49	19 09	8	Pac.	0.00 R	7.0	H_t	H
78	8/22/49	04 01	2	Pac.	0.00 R	8	H_p	H
79	11/3/49	01 13	19	Pac.	0.03 R	6½	V_p	H
80	11/22/49	00 52	12	Pac.	0.00 R	7.3	H_-	H
81	2/23/50	08 31	46	Pac.	0.06 R	6	H_t	K
82	2/28/50	10 21	46	Pac.	0.05 R	7½	H_t	H
83	3/27/50	13 05	1	Pac.	0.00 R	6½	H_p	H
84	5/17/50	18 13	14	Pac.	0.00 R	7	H_p	H
85	5/19/50	02 38	14	Pac.	0.00 R	6.9	H_p	H
86	5/19/50	07 05	14	Pac.	0.00 R	6½	H_p	H
87	5/25/50	18 35	17	Pac.	0.01 R	7.2	H_t	K
88	5/26/50	01 17	14	Pac.	0.00 R	7.3	H_p	H
89	5/27/50	12 40	14	Pac.	0.00 R	6½	H_t	H
90	5/28/50	01 37	14	Pac.	0.00 R	6½	H_-	H
91	6/21/50	06 56	14	Pac.	0.00 R	6½	H_p	H
92	6/24/50	22 25	14	Pac.	0.00 R	7	H_p	H
93	6/27/50	15 42	19	Pac.	0.00 R	6½	H_t	H
94	7/13/50	04 04	18	Pac.	0.08 R	6½	V_t	K
95	7/21/50	20 32	14	Pac.	0.00 R	6	V_p	H
96	7/22/50	23 08	14	Pac.	0.00 R	6	H_-	H
97	8/15/50	14 09	25	Med.	0.00 R	8.6	V_t	T
98	9/10/50	15 16	14	Pac.	0.04 R	7	H_p	H
99	12/2/50	19 52	14	Pac.	0.05 R	7.6	H_p	W
100	1/6/51	05 17	48	Med.	0.03 R	6.8	H_p	K
101	2/13/51	11 56	12	Pac.	0.03 R	6.9	H_p	H
102	3/10/51	21 58	14	Pac.	0.02 R	7.4	H_t	W
103	3/23/51	21 39	12	Pac.	0.04 R	7.2	H_t	H
104	4/16/51	19 53	18	Pac.	0.07 R	7	V_t	K
105	7/11/51	18 22	18	Pac.	0.07 R	7	V_p	K
106	8/10/51	23 00	46	Pac.	0.05 R	6½	H_p	K
107	8/28/51	16 31	12	Pac.	0.09 R	6½	H_t	H
108	2/11/52	07 01	24	Med.	0.10 R	7	H_t	R
109	2/14/52	03 38	24	Med.	0.00 R	7½	H_t	R
110	2/25/52	01 17	12	Pac.	0.00 R	6.9	H_t	H
111	3/4/52	01 23	19	Pac.	0.00 R	8½	V_t	K
112	3/9/52	17 04	19	Pac.	0.00 R	7½	V_t	K
113	3/19/52	10 57	22	Med.	0.00 R	7½	V_t	R
114	5/9/52	17 48	15	Pac.	0.01 R	7	H_p	H
115	5/28/52	07 59	19	Pac.	0.05 R	6.9	H_p	K
116	6/22/52	21 42	19	Pac.	0.00 R	7	H_t	K
117	7/13/52	11 59	14	Pac.	0.05 R	7	H_p	H
118	7/13/52	17 34	23	Med.	0.00 R	6½	V_p	R
119	7/21/52	11 52	3	Pac.	0.00 R	7½	V_p	G
120	7/27/52	08 23	12	Pac.	0.07 R	6½	H_p	H
121	9/11/52	22 27	12	Pac.	0.00 R	6½	H_-	H
122	11/4/52	16 58	19	Pac.	0.00 R	8½	H_t	H
123	11/29/52	08 23	19	Pac.	0.00 R	7.2	H_t	H
124	11/29/52	23 46	1	Pac.	0.00 R	6½	H_t	H
125	1/20/53	17 33	23	Med.	0.00 R	6½	H_t	R
126	2/25/53	21 16	1	Pac.	0.00 R	6½	H_t	H
127	3/5/53	21 01	19	Pac.	0.00 R	6½	H_-	H
128	4/6/53	00 36	24	Med.	0.00 R	7	H_t	R
129	6/25/53	10 45	24	Med.	0.00 R	7½	H_p	R

TABLE 1 - *Concluded*

No.	Date	GMT	Epicenter		Depth	M	Type	Ref
			Region no[a]	Seismic belt				
130	7/7/53	04 08	24	Med.	0.03 R	6½	V_p	R
131	8/9/53	07 41	30	Med.	0.00 R	6½	H_t	H
132	8/12/53	09 24	30	Med.	0.00 R	7½	H_t	H
133	8/12/53	12 05	30	Med.	0.00 R	6½	H_t	H
134	8/12/53	14 09	30	Med.	0.00 R	6	H_t	H
135	9/14/53	00 27	12	Pac.	0.00 R	6½	H_t	H
136	9/29/53	01 37	12	Pac.	0.04 R	7.2	H_p	H
137	10/5/53	04 32	19	Pac.	0.00 R	6½	H_t	H
138	11/13/53	16 17	24	Med.	0.00 R	6½	H_p	R
139	12/2/53	04 25	16	Pac.	0.00 R	6½	H_p	R
140	1/1/54	13 04	24	Med.	0.01 R	6½	H_p	R
141	2/20/54	18 35	24	Med.	0.09 R	6½	V_t	R
142	3/3/54	06 03	16	Pac.	0.00 R	7	H_t	R
143	3/22/54	23 42	25	Med.	0.02 R	7½	V_p	T
144	3/29/54	06 17	31	Med.	0.10 R	7½	H_p	H
145	6/6/54	16 51	16	Pac.	0.00 R	7	V_p	R
146	7/3/54	22 31	24	Med.	0.01 R	6½	V_p	R
147	9/20/54	00 39	23	Med.	0.00 R	6	V_p	R
148	10/3/54	23 22	23	Med.	0.00 R	6	H_p	R
149	11/2/54	08 24	24	Med.	0.00 R	6½	H_p	R

Key to references

A—*Adkins*; B—*Byerly*; D—*DiFilippo*; G—*Beniaff* and others; H—*Hodgson* and others; K—*Kogan* and others; M—*Honda, Masatuka* and others; W—*Webb* [*Scheidegger* 1955, 1956]; R—*Ritsema* [1956]; V—*Veldkamp*, to be published in de Bilt, Holland; T—*Tandon* [1955, 1956].

[a] The region numbers refer to those introduced by *Gutenberg* and *Richter* [1954].

New Guinea in the Pacific group. The total number of earthquakes of the Circum-Pacific Belt is 97, that of the 'Mediterranean' zone 52.

The shocks are also divided into three depth ranges, shallow 0–60 km (0.00 R), intermediate 60–300 km (0.01–0.04 R), and deep 300–750 km (0.05–0.11 R).

Presentation of the data—Table 2 gives the distribution of the different earthquake mechanisms in the two major seismic zones of the Earth.

Percentages of V_t, V_p, and H shocks have been calculated (V_- shocks proportionally distributed over V_t and V_p shocks), also percentages of T and P shocks (H_- shocks proportionally distributed over H_t and H_p shocks). These percentages are represented in Table 3 and Figure 2.

Results—In the shallow zones of both Pacific and 'Mediterranean', more than half of the shocks is of the H type. The percentage of these shocks, however, is far greater in the Pacific than in the 'Mediterranean'. Of the shocks with a more or less vertical plane of action the V_p shocks in both belts are in the majority over the V_t shocks. This is the more pronounced in the 'Mediterranean' zone. In both shallow zones the number of T and P earthquakes is about equal.

In the intermediate levels of the 'Mediterranean' zone V_p shocks dominate, in the Pacific belt the H shocks. In both zones V_t shocks are in the minority. The percentage of horizontal pressure shocks is always greater than that of the horizontal tension shocks. The difference is more pronounced in the 'Mediterranean' zone than in the Circum-Pacific Belt.

In the deep earthquake levels of the 'Mediterranean' zone V_t shocks dominate strongly over small percentages of V_p and H shocks. In the Circum-Pacific Belt the H shocks still are in the

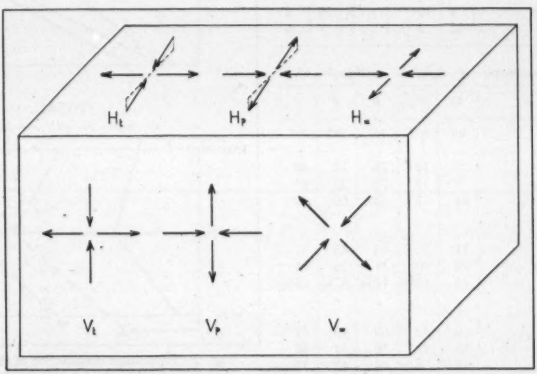

FIG. 1 - Typical examples of the different stress positions

majority but also here V_t shocks dominate over V_p shocks. The percentage of horizontal tension earthquakes of the 'Mediterranean' zone is far greater than that of the horizontal pressure shocks in the same zone. The same holds good for the deep earthquake level of the Circum-Pacific Belt, only the domination of T over P shocks is less pronounced here.

The general lines of the results so far reached are not influenced by an exclusion of the Japanese and Soviet data. The only difference is to be found in the deep earthquake level of the Pacific where only shocks of the H type remain of which two-third is of the P type and one-third of the T type. An exclusion of these data therefore means that the differences between 'Mediterranean' and Pacific earthquake mechanisms only tend to increase.

Conclusions—In the shallow zone of both seismic belts almost equal percentages of horizontal tension and of horizontal pressure earthquakes seem to occur.

The higher percentage of horizontal pressure earthquakes (P as well as V_p shocks only) at intermediate depth levels and the same of horizontal tension earthquakes (T as well as V_t shocks only) at deep earthquake levels seems to be inherent to both of the major seismic zones of the Earth.

The high percentages of transcurrent fault type earthquakes at all depth levels of the Circum-Pacific Belt as compared with the far smaller percentages of the same type shocks of the 'Mediter-

TABLE 2 – *Numbers of different earthquake types*

Type	V_t	V_p	V_-	H_t	H_p	H_-
Pacific						
Shallow	4	7	—	13	10	16
Intermediate	1	2	1	4	7	3
Deep	6	1	7	4	7	4
'Mediterranean'						
Shallow	3	10	—	8	5	2
Intermediate	3	8	—	1	3	1
Deep	6	1	—	1	—	—
Total						
Shallow	7	17	—	21	15	18
Intermediate	4	10	1	5	10	4
Deep	12	2	7	5	7	4

TABLE 3 – *Percentages of different earthquake types*

Type	V_t	V_p	H	T	P
	pct	pct	pct	pct	pct
Pacific					
Shallow	8	14	78	52	48
Intermediate	7	15	78	35	65
Deep	41	7	52	60	40
'Mediterranean'					
Shallow	11	36	53	43	57
Intermediate	19	50	31	26	74
Deep	75	12½	12½	87½	12½
Total					
Shallow	9	22	69	49	51
Intermediate	13	31	56	32	68
Deep	48	8	44	67	33

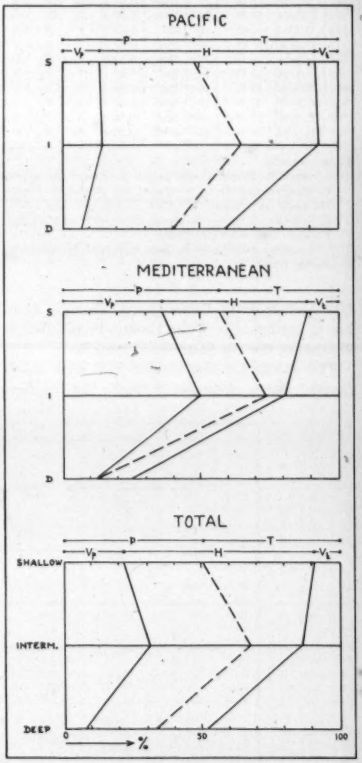

FIG. 2 – Percentage distribution of the different earthquake types in depth

ranean' zone seems to constitute a basic difference between the two major seismic belts of the Earth.

The data known at the moment indicate that an earthquake at any depth level of the Circum-Pacific Belt and at shallow depths of the 'Mediterranean' zone mostly results in a horizontal shortening of the fault rock combined with a horizontal lengthening perpendicular hereto [see also *Scheidegger*, 1955]. The only possible explanation of this is a differential moving of blocks in the Earth's crust and below as for example caused by pole deviations, by forces acting in consequence of the rotation of the Earth ("Polflucht"), or by a drifting of continental blocks with respect to oceanic blocks.

At the intermediate depth levels of the 'Mediterranean' zone an earthquake mostly results in a horizontal shortening of the fault rock combined with a vertical expansion, and at the deep earthquake levels of the same zone mostly a horizontal lengthening of the fault rock with a vertical shortening sets in. It is possible to bring the predicted fault movements as derived from the contraction theory of the Earth and from the convection theory of *Vening Meinesz* (1954) in line with these general features.

Only a combination of at least two of the theories mentioned here can explain all features of earthquake mechanisms as derived so far.

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A Case Study Bearing on the Origin and Propagation of 2- to 6-Second Microseisms*

William L. Donn

Abstract—A study of microseisms recorded at seven east-coastal and island stations for the hurricane of September 1–13, 1950, helps define the factors involved in the generation and propagation of storm microseisms. This study indicates (1) generation is poor over ocean areas characterized by uniform crustal thickness, and is very efficient over regions of strong thickness gradients; (2) efficient propagation seems limited to the crustal layer in which generation occurs. Further, a theory of microseism generation is proposed which involves the energy of waves breaking at sea as the exciting factor.

Introduction—This study is limited to microseisms generated in the western North Atlantic Ocean including the Caribbean Sea and the Gulf of Mexico. Although microseisms of seven to ten seconds have been recorded by stations in this region and have been described by many investigators, for example, *Carder* [1955], *Donn* [1954], and *Shurbet* and *Ewing* [1956], most of the microseism storms in the area fall into the two to six second range. The study of these microseisms has been restricted here to those of hurricane origin, owing to the small size of the generating area and the availability of fairly precise locations.

In past reports there has been considerable conflict of opinion concerning the efficiency of propagation of microseisms through continental and oceanic portions of the crust. The present study is directed at this problem, and inevitably touches on the problem of microseism origin, a problem in which even greater conflict of opinion prevails.

The case presented in this report is typical of the unambiguous cases studied for this region. Ambiguity is often introduced by the presence of several storm areas existing simultaneously or by the presence of local high winds.

With the exception of the Palisades station of Columbia University, all seismic data were obtained by seismographs of the Navy Microseism Project, the latter instruments being reported as having identical response curves which are essentially flat from four to seven seconds. The long-period Palisades-Columbia seismograph (whose response curves have been published elsewhere [*Donn*, 1950]), has peak response at 12 sec.

Microseism and hurricane data of September 1–13, 1950—In Figure 1, microseism amplitudes, as recorded at seven coastal and island stations, are plotted along the center track of the hurricane. Six-hourly storm positions are shown by short cross-hatches for which specific times can be reckoned from the time marked and actual trace amplitudes can be determined from the scale shown for each station. Although the period spectrum may be as broad as two to six seconds, the dominant microseism period at each station is indicated numerically at intervals along the storm track. The dotted line along coastal areas represents the 1000 fm depth contour which marks the approximate edge of the continental shelf zone. Circled symbols on the charts show the locations of the particular stations.

In Figure 2, hurricane intensity and area are plotted on opposite sides of the storm track. Intensity (as shown by pressure gradient) was measured along the shortest diameter of the storm. The area was taken within the isobar that enclosed a pressure gradient of at least 3 mb per degree. It is noteworthy that when maximum intensity occurred, between Puerto Rico and Bermuda, relative microseism quiet was observed at all of the coastal and island stations. The storm data of Figure 2, which are introduced for control, indicate that the microseism variations discussed below are, for the most part, a result of other causes than changes in storm conditions. The hurricane was clearly of adequate size and intensity to generate microseisms all along the track shown.

Data and discussion for coastal stations—The coastal stations of Palisades, Whiting, and Miami show nearly identical microseism patterns (Figure 1) despite the large distances among these stations and the different distance of each station from the hurricane. Peak amplitudes at these stations occur between 12h 30m and 18h 30m on September 12. It is clear from both the storm track and the synoptic weather chart at the lower right that this occurred when the hurricane cen-

* Contribution No. 242, Lamont Geological Observatory of Columbia University.

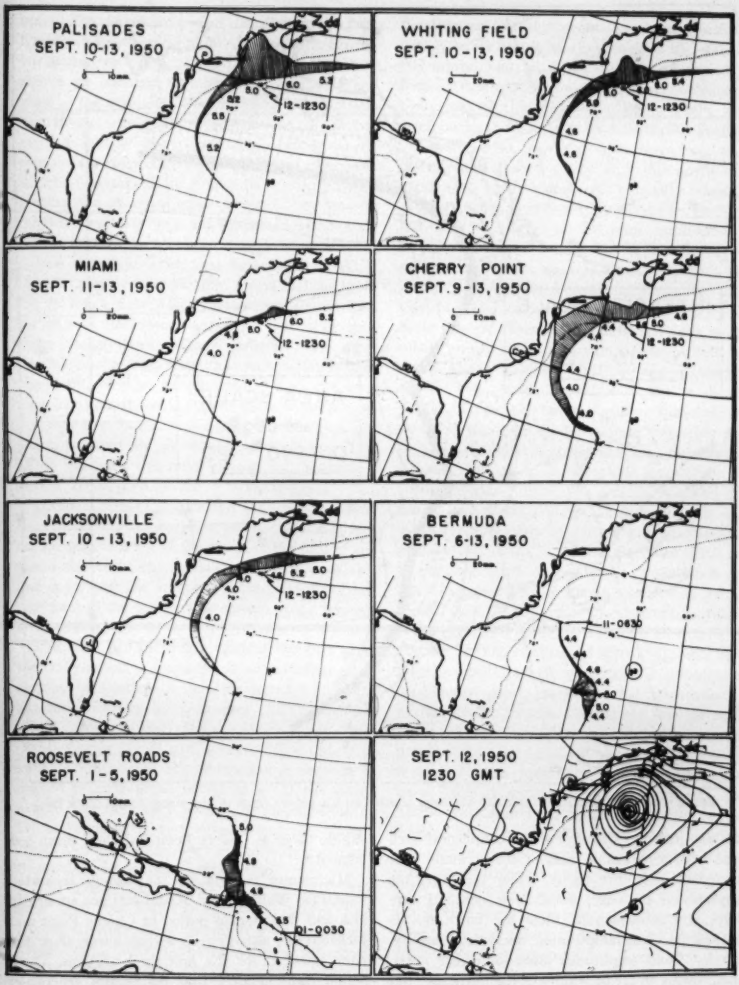

FIG. 1 – Microseism amplitudes plotted on the center track of the hurricane of September 1–13, 1950 for the stations shown; microseism period is indicated by numbers along the track; a marine weather chart is shown at the lower right for the time of maximum coastal microseisms

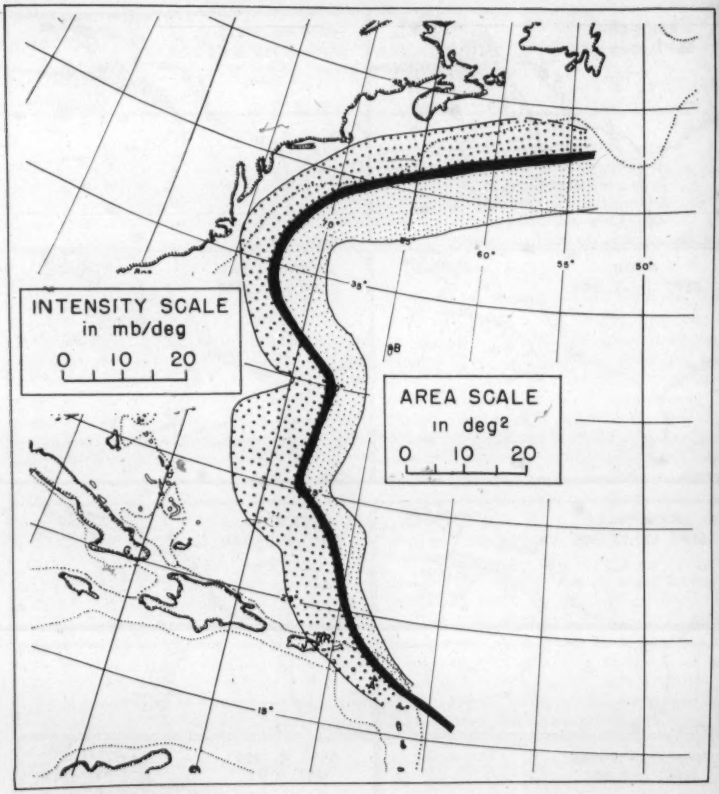

FIG. 2 – Graph of hurricane intensity and area plotted on the center track of the storm (solid black line)

ter was just over the edge of the continental shelf and with a maximum area of storm winds over the shelf zone. Previously, while the hurricane approached the edge, amplitudes increased rapidly; and subsequently, while the hurricane recurved to sea, amplitudes decreased rapidly. Cherry Point amplitudes reach an earlier maximum owing to the proximity of the hurricane, but amplitudes remained at close to maximum as the storm receded along the continental shelf. They then decline in the same manner as at the other three stations as the storm curved away from the edge of the continent. Jacksonville amplitudes resemble those at Cherry Point but show much less intensity.

Microseism periods at the widely separated Palisades, Whiting, and Miami stations are nearly identical. Microseism period at Cherry Point and Jacksonville, although somewhat lower, show the same trend as for the first three stations. These period data indicate that microseism generation is within the storm area, for if generated by local swell arriving from the hurricane, more distant stations should show longer periods. This is certainly not shown, for period among the stations is either the same or apparently unrelated to dis-

tance. The maximum period difference among the five coastal stations is about 1.5 seconds. Similar variations for different stations from the same source are common in microseism literature and may be the result of filtering during propagation, foundation conditions, or variations in instrument behavior apart from the theoretical response. The relatively high speed and change in direction of the storm might be argued as supporting the standing-wave origin of the coastal microseisms, but this is not supported by the data for the islands given below.

It is very interesting that amplitudes at Whiting, the most distant station, are as high as those for the much closer Cherry Point, and higher than for any of the other coastal stations. The synoptic chart (lower right) indicates no other possible source for these microseisms, and since the instruments are all reported to have the same magnification, it would appear that the thick sedimentary foundation at Whiting is especially sensitive to five- to six-second microseisms. This effect has been observed by the writer to be a normal occurrence for the Whiting station.

It should also be pointed out that the amplitude data are plotted along the track of the storm center for convenience. If the track of the half of the storm closest to the station were used (and this is a more realistic approach), the relation of microseisms to the continental margin would be even more striking.

The data for these five coastal stations show that microseism propagation is very efficient along continental borders, as well as across continents as shown earlier by *Gutenberg* [1921], *Ramirez* [1940], *Donn* [1954], *Donn, Ewing,* and *Press* [1954], *Carder* [1955], and others. These data also indicate that either (1) microseism generation is limited to continental margins, or (2) the continental edge acts as a barrier to propagation, or (3) propagation is very poor across the oceanic crust. As these factors are not mutually exclusive, they may exist in some combination.

Data and discussion for island stations—The data from the island stations at Puerto Rico (Roosevelt Roads) and Bermuda give further significant data. Maximum amplitudes at Roosevelt Roads occurred when the storm was closest to the station and declined to background when the hurricane center had receded only a few degrees to the north, but with the trailing half still very close to the island. This characteristic effect has been described earlier by *Gilmore* and *Hubert* [1948], who ascribed it to a microseism barrier. Considering the slow recession of the hurricane (note the six-hourly marks), swell in the wake of the storm must have buffeted the entire arc, as well as Puerto Rico, for an interval much longer than that of the microseism storm. Thus, local swell seems to be negated as a significant generating source. Also, standing ocean waves from wave interference is more likely with the storm over open water when microseisms were very weak.

Further, microseism amplitudes are surprisingly low with maximum double-trace amplitudes of about seven mm despite the proximity of the storm. This effect again is characteristic of this station, although the seismograph is reported identical in magnification with the others used by the Navy project. The weak Roosevelt Roads microseism intensity also contrasts strikingly with the much greater intensity of those coastal stations close to the storm, in addition to the distant Whiting, when the storm was over the continental shelf. Puerto Rico differs from this other area in the very narrow shelf zone that borders the island. These data lend further support to the theory proposed by *Ewing* and *Donn* [1952] and *Ewing* and *Press* [1952] that generation is only efficient in regions of strong crustal thickness gradient, for example, a shelf zone. The small size of this zone north of Puerto Rico would thus preclude the generation of strong microseisms there.

The data for Bermuda show maximum microseisms occurring with the hurricane closest to the station, having commenced after those at Puerto Rico reached background, and the symmetrical distribution again suggests that generation is within the storm area. During the time of maximum microseisms at Bermuda the hurricane was nearly stationary for about two days. This seems to obviate the possibility of wave interference from different sectors of a traveling storm, and hence generation from resulting standing waves. Also, none of the coastal stations on the mainland recorded microseisms while those of high intensity were generated near and recorded at Bermuda. And no microseisms were recorded at Bermuda when they were generated near the east coast. The latter is contrary to data reported for seven- to ten-second microseisms by *Shurbet* and *Ewing* [1956].

When the entire hurricane area was about midway between Bermuda and Puerto Rico, no storm microseisms were recorded at either station despite the relative short distances. Bermuda microseisms commenced when the forward part of the storm approached the Bermuda Rise. As the

Bermuda platform is essentially oceanic, and microseisms are propagated quite well across it, it seems that lack of efficient generation rather than poor propagation is the explanation for the microseism quiet when the hurricane was over the abyssal zone. Further, the absence of microseisms at Bermuda and coastal stations when the hurricane was between these areas may again be explained by lack of generation.

To continue this reasoning, it is noted again that the strong microseisms generated near Bermuda were not registered at coastal stations, nor at Puerto Rico. If propagation across the Bermuda platform can be considered oceanic, then this lack of registration appears to be the result of a barrier effect at the continental and island arc boundary zones.

Discussion and conclusions—Microseism generation seems to be very inefficient over the abyssal plains of the oceans which have a uniformly thick crust, in contrast to the very efficient generation over zones where strong crustal thickness gradients exist. The broader is this zone, the more intense are the resulting microseisms.

Efficient propagation seems to be limited to the crustal medium or layer in which generation occurs as a result of a barrier effect in the vicinity of the boundary zones of continents and island arcs. The efficiency of propagation across the oceanic crust appears to be partly but incompletely settled by the Bermuda data. Short of ocean-bottom seismographs a comparison of microseisms at two islands with ocean crust foundations is necessary to provide a firm test for the question of ocean propagation. One such island alone is necessary but not sufficient for a positive statement concerning propagation through ocean crust for it may not be perfectly valid to consider propagation across the Bermuda platform as equivalent to that across ocean crust.

Theories of microseism origin proposed to date may be summarized as (a) effects of surf in shore zones; (b) effects on the bottom from progressive swell; (c) effects of atmospheric oscillation on the sea surface; and (d) effects of standing waves on the sea bottom. Although empirical data have been presented to support one or another of these explanations, no single one seems capable of anything like universal application.

The case just presented seems to negate both surf and standing waves as generating sources and the pressure effects on the bottom from surface waves and swell have been shown to be generally negligible. Although *Whipple* and *Lee* [1935] suggested, and the writer [*Donn* 1951, 1952] elaborated the idea that microseisms may be excited from the impulsive effect of atmospheric oscillations on the sea surface, it has been maintained by some, for example, *Haskell* [1953], that such a mechanism would not impart the required energy to the ocean surface. This idea was supported by the observed greater efficiency of cold wind in generating microseisms [*Jones*, 1949; *Donn*, 1951, 1952; *Båth* 1953], for air that is cold relative to the sea has a more turbulent structure than warm air.

It is also known, however, that cold wind generates ocean waves more readily than does warm [for example, *Roll*, 1952; *Fleagle*, 1956] and that in general the threshold wind speed for microseism generation is about 15 knots, although the specific intensity and time of commencement of microseisms varies with the relation between sea and air temperatures, as noted above. This threshold wind speed is also the speed at which whitecaps or breaking waves become widespread over the water surface.

The hypothesis is now proposed that microseisms of the type under discussion are generated by waves breaking at sea. This energy, which, when integrated over a storm area, can be considerable, would produce a very high random noise level in the ocean; the latter, probably including the loose bottom, would act as a filter in transmitting the energy, resulting in some period-depth relation.

According to this idea, surf is a limited case of breaking waves. It is probable that the surf area itself is usually too small for significant microseism generation, but when continued seaward into a possible broad area of breaking waves, strong microseisms can occur. Strong surf alone has been shown in the New England area by *Donn* [1953] to generate barely recognizable microseisms in the period range considered here.

Although a quantitative treatment of this hypothesis is deferred for separate treatment, the proposed mechanism seems to harmonize much of the conflicting data bearing on origin. For the most part, data supporting the surf mechanism of origin come from observations on the west coasts of continents, whereas observations on the east coast tend to negate this mechanism. Strong surf usually commences on a west coast essentially simultaneous with the generating westerly and relatively cold wind. Thus a very large region of

unstable breaking waves exists seaward from the surf zone. However, on eastern coasts, strong surf is usually the result of warm southerly or southeasterly winds, and results essentially from the approach of stable swell. This surf zone, which has no large seaward extension, is rarely associated with significant microseisms. On the other hand, a broad area of cold air moving seaward, with or without previous high surf, seems always to generate relatively intense microseisms whose amplitudes increase as the generating area spreads seaward. The cold wind raises waves beyond the stable height (1:7 for height to wave length) very quickly.

This relation of cold wind to breaking waves also seems to explain the cases which supported the idea of atmospheric oscillations being the generating mechanism. Further, regions of strong wave interference could also be areas of high breaking wave activity.

This hypothesis, which seems to harmonize the conflicting data bearing on microseism origin, will be considered further in a subsequent paper. Further studies of microseism propagation are also under way.

Acknowledgments—The writer is very grateful to M. H. Gilmore, in charge of the Navy Microseism Research Project, for making available a large number of seismograms and data. Weather data were obtained from the Ocean Forecast Section of the U. S. Weather Bureau at the New York International Airport.

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Isotopic Ages of Zircon from Granites and Pegmatites

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Abstract—Isotopic lead age determinations have been made on 13 zircons obtained from rocks 185 to 1400 million years old. Concordant or nearly concordant ages are found for all of the samples which contain no detectable common lead, and discordant ages are found for most, if not all, of the samples which contain common lead. A comparison is made between the concordant isotopic age patterns given by three zircons from the Grenville subprovince in Ontario and the discordant patterns given by three zircons from the Cordilleran region of western United States. This indicates that the discordant ages can be related to the recent orogenies which occurred in the Cordilleran region. The Grenville is a stable shield area. There is no relation between the agreement of the isotopic ages of zircon and crystal size, amount of radiation damage or optical appearance—that is, zoning, cloudiness, or inclusions.

When a discordant age result is compared with the potassium-argon and rubidium-strontium ages of associated mica the Pb^{207}–Pb^{206} age is found to be the closest to the mica age. Isotopic ages are compared with the simpler alpha-lead and chemical lead ages, which do not require isotopic analysis of lead. The non-isotopic ages are approximately correct for zircons which have concordant isotopic ages but are in error when discordant isotopic ages are found. No explanation is offered as to why the mica ages are apparently unaffected by the process or processes which altered the zircon ages. An understanding of this phenomenon would doubtless provide valuable information concerning the post-crystallization history of the samples.

Introduction

Nearly fifty years ago Lord Rayleigh [*Strutt*, 1910] focused attention on the radioactivity of zircon and attempted to measure the ages of specimens of this mineral from granites and pegmatites. He determined the uranium, thorium, and helium contents of 14 samples and showed that zircons from older rocks contained proportionately more helium in relation to uranium and thorium than did those from younger rocks. As knowledge in the field of geochronology has increased it has become apparent that the retention of helium by zircon may not be complete and that the reliability of the helium method is questionable.

More recently Larsen has devoted considerable effort to studies aimed at establishing a lead method of age determination based on zircon. His early work culminated in the paper of *Larsen, Keevil*, and *Harrison* [1952] in which a method based on the alpha activity and total lead content of zircon was presented. Zircon was selected on the expectation that primary lead would be excluded from the lattice at the time of crystallization owing to the large difference in the ionic radii of zirconium and lead. This was partially verified, at least, by the low concentration of lead found in zircons of Miocene age. It was Larsen's hope that this method would measure the age of a zircon with an error of less than ten per cent for most samples. He recognized that such a method would be of tremendous service to geology because of its relative simplicity. The data seemed to support these initial hopes.

The results obtained by the alpha-lead method were compared with ages based on separate chemical determinations of uranium and thorium in the paper by *Larsen, Waring*, and *Berman* [1953] for a zoned Precambrian zircon from the Wichita Mountains in Oklahoma. They obtained close agreement between the alpha counting and chemical methods and found, furthermore, that separate fractions of the zircon with radioelement concentrations which differed by nearly a factor of ten gave similar age values.

Tilton and others [1955] presented the first isotopic age measurements on zircon in a study of the distribution of uranium, thorium, and lead in a Precambrian granite from Tory Hill, Ontario. No primary lead could be detected in the zircon. The two uranium-lead ages agreed within the limits of error, while the thorium-lead age was lower than these ages by more than a factor of two. The alpha-lead age, controlled primarily by the uranium-lead ages, agreed with a number of concordant age measurements within ten per cent.

The present paper gives the results of isotopic age measurements on 12 additional zircons and compares these ages with those obtained by the simpler alpha-lead method. The problems which arise from discordant isotopic ages will be discussed.

Experimental

Stable isotope dilution techniques have been used for all of the analytical results reported in this paper, except in the case of the Ceylon zircon, for which a colorimetric procedure was used for thorium. The techniques for uranium and lead have been described by *Tilton* and others [1955] and those for thorium by *Tilton*, *Aldrich*, and *Inghram* [1954]. Only a brief summary of the final procedures used will be given here.

A 200–400 mg sample of zircon of grain size not exceeding 100 mesh was fused in about five grams of borax. The resulting glass was digested in 6M hydrochloric acid to precipitate most of the silica which was collected by centrifuging. The supernate was transferred to a 250 ml volumetric flask. The silica was removed by hydrofluoric and perchloric acid digestion, and the resulting solution was added to the original solution in the volumetric flask, the contents of which were diluted to the mark with double-distilled water.

Two aliquots, each containing 10–30 μg of lead, were taken. Twenty μg of 95 pct Pb^{208} tracer were added to one aliquot. The second aliquot was processed without tracer. Lead was recovered from the aliquots by dithizone extractions at a pH of 8.5–9, first in the presence of ammonium citrate and then in the presence of potassium cyanide. Mass spectrometer analyses were made by the lead sulfide method described by *Aldrich*, *Wetherill*, *Tilton*, and *Davis* [1956].

For the uranium and thorium analyses a single aliquot usually containing 10–50 μg of uranium and somewhat less thorium was equilibrated with 6 μg of 99.9 pct U^{235} tracer and 8 μg of 90 pct Th^{230} tracer. The hydroxides were precipitated by bubbling ammonia gas into the solution. The collected precipitate was dissolved in a few drops of concentrated nitric acid. A 15 pct solution of nitric acid saturated with aluminum nitrate enneahydrate was added and the uranium and thorium extracted into hexone. Uranium and thorium were stripped from the hexone with water, the aqueous solution evaporated nearly to dryness, and a solution of saturated (10M) ammonium nitrate was added. A second hexone extraction was made and the uranium and thorium were recovered once more with water. This extract was evaporated to dryness for the mass spectrometric analyses. Uranium emission occurred first in the spectrometer runs and after the uranium had almost completely evaporated the thorium peaks were obtained.

The recovery of uranium from the ammonium nitrate extraction was about 90 pct, while that for thorium was only about 30 pct. However, this procedure yielded sufficient thorium for satisfactory runs, since the mass spectrometer was equipped with an electron multiplier. In general, the thorium results were not as good as those obtained by the lengthier procedures described by Tilton, Aldrich, and Inghram, but the accuracy seemed adequate for the present purpose. By the new procedure the thorium and uranium could be determined simultaneously instead of requiring separate chemistry and mass spectrometry.

Loss of lead to platinum during fusions—It was found that there was a tendency for lead to enter the platinum crucibles during fusions in spite of the usual precautions of using a Meker burner equipped with an air blast and keeping the crucible well above the reducing part of the flame. This was presumably due to the reduction of lead to the metallic state by incompletely oxidized burner gas, the lead then diffusing into the platinum. Several experiments were performed which relate critically to the age results, since loss of lead to the platinum may give an erroneous indication that zircon has lost lead in its natural environment.

The first two experiments each involved the addition of carrier-free Pb^{210} activity to three grams of borax (containing about two parts per million of lead) in a platinum crucible placed about three inches above the reducing part of the flame of a Meker burner with an air blast, fusing the mixture for 12 minutes without a cover and then for three minutes with a cover. The borax glass was dissolved in 1.5 M hydrochloric acid, approximately 20 μg of shelf lead added, and the lead recovered by dithizone extractions after bringing the pH to 9 with ammonium citrate and ammonium hydroxide. The chloroform solutions containing the lead dithizonates were evaporated to dryness on glass planchets for counting. The first experiment gave a 94 pct recovery of lead activity. A count of the crucible in roughly the same geometry as the glass planchet, which had an activity of 5000 cpm (counts per minute), gave an activity of 330 cpm. The second experiment showed a lead recovery of 96 pct., the planchet having an activity of 5150 cpm and the crucible an activity of 10 cpm. Handling losses in these experiments were probably as much as two or three per cent. It was concluded that the fusions described could produce a possible loss of

lead of one to three per cent. Such a loss would not be considered serious since the analytical errors for lead determinations are about ± 2 pct.

In other work some zircon samples were encountered which required 60–90 minutes of fusing rather than 15 minutes; consequently a more elaborate experiment was made to test these longer fusions. The starting material was a finely ground sample of Hybla cyrtolite, part of which had been analyzed previously for uranium, thorium, and lead, using a five-minute fusion. A 400 mg sample was fused 90 minutes with carrier-free Pb^{210} activity in ten grams of borax. The crucible was covered throughout the fusion and was placed about two inches above the reducing part of the flame of a Meker burner, duplicating the conditions of the longer fusions used for the zircons. After the glass was dissolved in hydrochloric acid three separate aliquots were taken. One was 'spiked' with Pb^{208} and analyzed for lead concentration. A second aliquot was analyzed for the concentrations of uranium and thorium. Sixteen mg of lead was added to the third aliquot in order to determine the recovery of lead activity. The lead in this solution was precipitated as lead sulfate, dissolved in ammonium acetate, and then precipitated as lead chromate. The lead chromate was filtered, washed, weighed to determine handling losses during the precipitations, then mounted for counting. The results for the long and short fusions are compared in Table 1. The yield of lead activity was 93 ± 2 pct, whereas the losses of uranium and thorium were apparently negligible.

From these experiments it has been concluded that a liberal estimate of the loss of lead to platinum would be as much as two per cent in a 15 minute fusion, and five to ten per cent in a fusion of an hour or longer. These estimates will be considered in discussing the age results in a later section. The lead activity is strongly held once it enters the platinum. Flaming the crucible followed by boiling in concentrated nitric acid has little effect on its activity.

TABLE 1 – *Effect of length of fusion on a standard sample of Hybla cyrtolite*

Length of fusion	Concentrations in parts per million			
	Uranium	Thorium	Pb^{204}	Pb^{204} corrected for Pb^{210} yield
min				
5[a]	4177	2461	858	(858)
90	4190	2524	818	878 ± 15[b]

[a] Determination by Henry Faul.
[b] Includes only the error in the Pb^{210} yield.

It was noticed that the zircons which required long fusions decomposed in a characteristic manner. Most of the material disappeared in the first five to ten minutes but a white granular residue remained which settled to the bottom of the melt. This residue decomposed very slowly, usually requiring an hour or more of fusion. Recent studies by Faul at this Laboratory have shown that if this white material is removed from the melt at the time most of the material has dissolved, placed in fresh borax and fused separately, it will decompose in five or ten minutes. This is probably a better way to decompose these zircons.

The method used for the removal of pyrite varied in the course of the work. The Tory Hill granite, Bagdad, and Quartz Creek granite 'A' samples were freed from pyrite by roasting the zircon concentrates at 400° C for five minutes, which coated the pyrite with a magnetic oxide and allowed it to be removed by a Frantz magnetic separator. The other samples were purified by treating the zircon fractions for 30 minutes with concentrated nitric acid held just below the boiling point. The latter procedure is believed to be preferable.

Source and Petrographic Description of Samples

(1) Redstone, New Hampshire. Collected from the quarry at Redstone, north of Conway, N. H.

The zircon used in this study was separated from the 'green' granite. The granite belongs to the White Mountain Series, which is the youngest of the four magma series recognized by Billings. Crystal size 200–350 mesh; zoning not common; refractive index (ω) = 1.92; birefringence high; crystals clear; half of crystals have one or more anhedral inclusions; little cloudiness or staining.

(2) Wichita Mountains, Oklahoma. Taken from a pegmatite body at Quanah Mountain in the Wichita Mountains, Comanche County, Okla. The geology of the area has been discussed by *Hamilton* [1956]. The large zircon crystals are distinctly zoned, some parts being 'fresh' and others 'metamict.' A sample of each part was supplied by David Gottfried of the U. S. Geological Survey.

Sample 'A,' 'metamict:' ω generally low, about 1.82; half isotropic, remainder low birefringence except for several per cent of fresh crystals; brown-black cloudiness nearly masking the birefringence for half of the crystals, some nearly opaque; brownish staining frequent; inclusions rare.

Sample 'B,' 'fresh:' $\omega = 1.92$; birefringence high except for several per cent of metamict crystals; little cloudiness or staining; inclusions rare.

(3) Ceylon. Obtained from H. D. Holland of the Department of Geology, Princeton University. (Sample Zr 2-47.) The sample was part of a single crystal of gem-grade material. Crystal size about one cm; not zoned; $\omega = 1.91$; birefringence high; crystals clear; inclusions and staining absent.

(4) Capetown, South Africa. Collected by L. O. Nicolaysen at the Lower Cable Station in Capetown. Crystal size 200–350 mesh; zoned; $\omega = 1.92$; birefringence high; crystals clear; inclusions and staining rare.

(5) Tory Hill, Ontario, granite. This sample is described in the paper of *Tilton* and others [1955]. The granite was collected by a party under the late H. V. Ellsworth on the Brower property north of Tory Hill. The exact location is unknown. Crystal size 0.5–1.0 mm; zoning extensive; refractive index variable, 1.82–1.85 for metamict and about 1.91 for fresh zones; birefringence variable with more metamict crystals nearly isotropic; inclusions rare; brown stains common; about half of crystals cloudy to nearly opaque.

(6) Tory Hill, Ontario, syenite. Collected at the opening marked 'Ra' on the map of *Satterly* [1943], one mile north of Tory Hill on the old road to Essonville. The new road passes about 50 ft east of the old road at this point. The opening is located on the Brower property. Crystal size 200–350 mesh; zoned; ω generally about 1.91; high birefringence; crystals mostly clear, about 20 pct with brown-black cloudiness; inclusions rare.

(7) Cardiff Uranium Mine, near Wilberforce, Ontario. The specimen was taken from loose waste at the north adit of the mine, located about two miles southeast of Wilberforce. The zircon occurs with pyroxenite and calcite. Much uraninite is also present in the pegmatite. *Satterly* and *Hewitt* [1955, p. 15] have given a description of the mine. Crystal size 3–5 mm; zoned; ω low, about 1.83; birefringence variable; few inclusions; brownish staining common.

(8) Natural Bridge, New York. Obtained from H. D. Holland and A. F. Buddington of the Department of Geology, Princeton University. The sample was half of a large gem-grade crystal found on the Ashmore farm where it occurred in limestone near a syenite contact. Crystal size about one cm; not zoned; $\omega = 1.91$; birefringence high; crystals clear; inclusions absent.

(9) Pike's Peak, Colorado. Collected from a road-cut two miles northwest of Manitou Springs on U. S. Highway 24. This is the lower of the two Pike's Peak granites. Crystal size 200–350 mesh; zoned; $\omega = 1.92$ for fresh, lower for metamict zones; birefringence high; crystals generally clear, several per cent dark and cloudy; half of crystals have small anhedral inclusions.

(10) Llano, Texas. Collected at the Petrick Quarry on the west shore of Lake Buchanan, Llano County, Texas. Crystal size 100–350 mesh; zoned; $\omega = 1.92$ for fresh, lower for metamict zones; birefringence variable; brown-black cloudiness nearly masking the birefringence for most crystals; brownish stains common; inclusions rare.

(11) Bagdad, Arizona. The granite was collected from the Lawler Peak area near Bagdad. Crystal size 200–350 mesh; zoned; ω variable, about 1.87; birefringence generally high; brown-black cloudiness nearly masking birefringence for half of crystals, remainder clear; small anhedral inclusions fairly common. The zircon concentrate contained about five per cent of xenotime.

(12) Quartz Creek District, Colorado. Granite 'A' was collected one mile to the west of the Brown Derby Mine near Gunnison. Granite 'B' was collected five miles to the south of the Brown Derby Mine from a road-cut along U. S. Highway 50 between Doyleville and Parlin. The micas and feldspars were fresh in granite 'B' in contrast to those from granite 'A,' which were badly altered. The two granites are believed by *Staatz* and *Trites* [1955, p. 7] to be parts of the same granite body. A complete description of the uranium-lead, potassium-argon, and rubidium-strontium work in the Brown Derby area has been published by *Aldrich*, *Davis*, *Tilton*, and *Wetherill* [1956]. The petrographic description below applies to zircon from both granites. Crystal size 200–350 mesh; zoned; ω about 1.88; birefringence high; brown-black cloudiness nearly masking birefringence for most crystals; brownish stains fairly common; inclusions rare.

Results

The analytical data together with the ages for the 13 samples of zircon are given in Tables 2 and 3. Several of these results have been published in previous papers: Tory Hill granite [*Tilton* and others, 1955], Quartz Creek granites [*Aldrich*, *Davis*, *Tilton*, and *Wetherill*, 1956], Capetown and Bagdad granites [*Aldrich* and others, 1955]. The remaining results are new.

TABLE 2 – *Analytical data*

Sample	Concentration in parts per million				Atom per cent abundance relative to Pb^{204}			
	Uranium	Thorium	Lead	Pb^{204}	Pb^{204}	Pb^{206}	Pb^{207}	Pb^{208}
Redstone, N. H., granite	1113±11	375±5	32.5	28.0±1.0	...	100	4.85±0.15	11.25±0.11
Wichita Mts., Okla., pegmatite	2062±20	8120±80	376	156.0±2.3	0.295±0.006	100	10.10±0.10	1.29±0.01
Wichita Mts., Okla., pegmatite	414±4	1337±13	63.5	30.7±1.0	0.121±0.003	100	7.58±0.08	1.03±0.01
Ceylon, pegmatite	1550±15	183±3	127	115.4±2.9	...	100	5.83±0.06	3.83±0.04
Capetown, S. Africa, granite	1065±15	177.5±2.5	66.5	51.3±1.3	0.365±0.06	100	11.17±0.12	17.75±0.18
Tory Hill, Ont., granite	2650±40	2180±20	461	392±10	...	100	7.49±0.12	9.68±0.18
Tory Hill, Ont., syenite	781±8	...	123	104.6±2.1	...	100	7.22±0.07	10.79±0.11
Cardiff Uranium Mine, Ont., pegmatite	3460±35	232±4	485	442±6	...	100	7.15±0.07	2.36±0.03
Natural Bridge, N. Y., contact	774±8	...	127	113.8±2.3	...	100	7.68±0.08	4.04±0.10
Pike's Peak, Colo., granite	277±3	319±5	33.3	24.8±1.0	0.174±0.005	100	9.60±0.10	26.0±0.3
Llano, Texas, granite	337±3	122±3	53.8	45.4±0.8	...	100	7.40±0.08	10.97±0.10
Bagdad, Ariz., granite	2950±40	1413±30	338	269±10	0.215±0.007	100	10.98±0.25	14.33±0.42
Quartz Creek, Colo., granite A	1041±12	281±20	210	150±5	0.512±0.019	100	16.46±0.45	22.78±0.64
Quartz Creek, Colo., granite B	...	...	...	...	0.557±0.008	100	17.80±0.18	31.51±0.32

TABLE 3 – *Age results for zircons and associated micas*[a]

Sample	Crystal size	Length of fusion	Common lead content	Zircon age in million years				Mica age in million years	
				U^{238}–Pb^{206}	U^{235}–Pb^{207}	Pb^{207}–Pb^{204}	Th^{232}–Pb^{208}	Rb^{87}–Sr^{87}	K^{40}–A^{40}
		min	*ppm*						
Redstone, N. H., granite	200–350 mesh	45	≦0.4	187±5	184±5	140±60	190±5	185	182
Wichita Mts., Okla., sample 'A,' pegmatite	1–2 cm.	10	33	520±12	527±10	550±30	506±12	500	480[b]
Wichita Mts., Okla., sample 'B,' pegmatite	1–2 cm.	45	2.6	514±12	522±10	550±20	493±12	..	..
Ceylon, pegmatite	1–2 cm.	80	≦1.7	540±12	544±16	555±30	538±25	..	..
Capetown, S. Africa, granite	200–350 mesh	45	14	330±10	356±15	530±50	238±20	600	530
Tory Hill, Ont., granite	0.5–1 mm.	12	≦5.5	1030±25	1050±15	1090±25	390±15	..	..
Tory Hill, Ont., syenite	200–350 mesh	75	≦1.5	940±25	960±15	1015±25	...	..	..
Cardiff Uranium Mine, Ont., pegmatite	3–5 mm.	15	≦6	900±25	930±15	1000±25	990±50	1030	1010
Natural Bridge, N. Y., contact	1–2 cm.	90	≦1.6	1025±25	1065±20	1140±50	...	..	..
Pike's Peak, Colo., granite	200–350 mesh	35	3	624±25	707±20	980±40	313±12	1020	1030
Llano, Texas, granite	100–350 mesh	60	≦0.6	950±25	990±15	1070±25	890±40	1100	1090
Bagdad, Ariz., granite	200–350 mesh	15	40	630±20	770±30	1210±80	271±16	1390	1410
Quartz Creek, Colo., granite 'A'	200–350 mesh	15	54	925±25	1130±25	1540±140	530±110	..	..
Quartz Creek, Colo., granite 'B'	200–350 mesh	15	...	...	...	1700±60	...	1310	1325

[a] Uncertainties in lead ages include all analytical errors except those due to possible loss of lead to platinum during fusion. For samples fused 60 minutes or longer the lead concentrations may be low by five to ten per cent, consequently the U^{238}–Pb^{206} and Th-Pb^{208} ages may be proportionately low.

[b] Biotite from granophyn, Laae Altus Reservoir.

Effect of contamination from chemical processing on age results—Uranium and thorium blanks consistently ran about 0.01 μg. Since the uranium and thorium analyses were made on 30–50 mg of zircon in all cases, these blanks affected the final uranium results by less than one per cent and affected about half of the thorium results by one per cent at most and the remainder by two or three per cent. Lead blanks, which ranged from 0.3 to 1.3 μg and averaged about 0.5 μg, had considerably more influence on the lead concentrations. Lead analyses for concentration and isotopic composition were made on samples weighing about 150 mg each; therefore, the blanks caused corrections of about one ppm (part per million) for the Pb^{206} and Pb^{207} concentrations and about two ppm for the Pb^{208} concentrations. The magnitude of these corrections may be estimated from the analytical data in Table 2. An attempt has been made to adjust the uncertainties in the Pb^{206} concentrations in Table 2 to include effects due to the blanks. For example, the blank had no

serious effect on the lead concentration of the zircon from the Cardiff Uranium Mine (442 ppm Pb^{206}), but it introduced greater uncertainty into the result from the sample from the Pike's Peak granite (25 ppm Pb^{206}). It should be noted that this has only a secondary effect on the accuracy of the age because the common lead corrections were much the same whether this lead came from laboratory contamination or was actually contained in the mineral.

The decay constants used in calculating the ages in Table 3 are those which are in common use, namely: U^{238}, 1.54×10^{-10} yr^{-1}; U^{235}, 9.72×10^{-10} yr^{-1}; Th^{232}, 4.99×10^{-11} yr^{-1}. The present day ratio, U^{238}/U^{235}, was taken as 137.8.

Discussion

For the purpose of this discussion, when the U^{238}-Pb^{206}, U^{235}-Pb^{207}, and Pb^{207}-Pb^{206} ages for a zircon agree within ten per cent, the ages will be considered to be in agreement within the limitation of the analytical method. When they differ by more than ten per cent, they will be considered to be discordant. Instrumental considerations alone limit the accuracies of the ages to about three per cent. The remainder of the uncertainty arises from the possibility of loss of lead to the platinum crucibles during fusion as was discussed in a previous section. Using this ten per cent criterion, the various uranium-lead ages are in agreement for the Tory Hill granite and syenite, the Cardiff Uranium Mine, Natural Bridge, Ceylon, Redstone, and Wichita Mountain samples. They do not agree for the Capetown, Bagdad, Quartz Creek, and Pike's Peak samples. The ages at Llano are slightly outside this limit of agreement.

For the zircons whose uranium-lead ages are in disagreement, the question arises as to which, if any, of the various ages are correct. Potassium-argon and rubidium-strontium age determinations have been made in these laboratories on micas associated with seven of the zircons. The results of these studies are summarized in the last two columns of Table 3. A more complete discussion of this work will be given in a separate paper. The mica ages are calculated using decay constants of 1.39×10^{-11} yr^{-1} for the beta decay of Rb^{87} [*Aldrich, Wetherill, Tilton,* and *Davis,* 1956] and 5.57×10^{-11} yr^{-1} for the electron capture process and 4.72×10^{-10} yr^{-1} for the beta decay process of K^{40} [*Wetherill* and others, 1956].

Agreement of potassium-argon and rubidium-strontium ages is probably a better indication of absolute age than is agreement of the two uranium-lead ages, the criterion which has been widely used in the past. The use of concordant uranium-lead ages for absolute age depends for the most part on the difference in half-lives of U^{238} and U^{235} which decay to lead in each case. Potassium and rubidium decay to two chemically different daughters, strontium and argon, which might be expected to behave quite differently during any processes affecting their concentrations in the host mica. The age of a mica will be considered to be known when the potassium-argon and rubidium-strontium ages agree.

Two facts appear regarding these age comparisons. The concordant potassium-argon and rubidium-strontium ages at Redstone, Cardiff, and Llano are in good agreement with the nearly concordant ages given by the zircons. The rubidium-strontium and potassium-argon discordancy for the Capetown granite probably indicates some argon loss. In the remaining cases where the uranium-lead ages are discordant the Pb^{207}-Pb^{206} ages agree more closely with the potassium-argon and rubidium-strontium ages than do any of the others. The Pb^{207}-Pb^{206} age is lower than the mica ages at Bagdad and is higher at Quartz Creek. It should be emphasized that, in view of these observations, the Pb^{207}-Pb^{206} age may be incorrect when discordant ages occur. Thus a Pb^{207}-Pb^{206} age from a single discordant age determination is not sufficient to establish the age with certainty.

The foregoing discussions have not considered the thorium-lead ages. With the exception of the Cardiff, Ceylon, and Redstone results, the thorium-lead ages all seem to be too low. The thorium-lead result at Tory Hill and Pike's Peak, for instance, would place these granites in the post-Cambrian and are obviously in error. If the thorium-lead ages are low, it is reasonable to believe that the uranium-lead ages have been lowered by the same mechanism regardless of its exact nature. This line of reasoning favors the Pb^{207}-Pb^{206} ages over the U^{238}-Pb^{206} and U^{235}-Pb^{207} ages in the case of discordancies.

Although the present data are limited, two interesting relations are now apparent in the uranium-lead ages. There is a definite relation between the common lead content and the uranium-lead ages in Table 3. When the amount of common lead found was about that which could be accounted for by the blank, the U^{238}-Pb^{206} and Pb^{207}-Pb^{206} ages of the sample agreed within approximately ten per cent. The Capetown, Bagdad, and Quartz Creek samples which gave discordant ages contained amounts of common lead which defi-

nitely exceeded the amounts to be expected from the blanks. Since the Pike's Peak sample was so low in radiogenic lead, it is more difficult to determine whether the common lead found actually came from the crystals or from contamination in the processing exceeding the lead measured by the blank. It is probable that the sample did contain common lead since the blank would have to be doubled in order to account for all the common lead found. The Wichita Mountain samples are the only exception to this relation.

The question of impurities in the zircon samples arises. With the exception of the Bagdad sample, which contained about five per cent of xenotime, no impurities except inclusions were noted in any of the concentrates. In the case of the Quartz Creek concentrate from granite 'A,' it was thought that perhaps the roasting process had not been efficient in promoting the removal of sulfides. In consequence a concentrate was prepared from granite 'B,' and the sulfides were decomposed by prolonged digestion in hot concentrated nitric acid. The leads obtained in the two processes were remarkably similar, as can be seen in Table 2. This would indicate that the common lead in the samples cannot be removed by hot nitric acid and cannot, of course, be due to the presence of sulfide impurities. The grains were relatively free from inclusions. In each case about ten per cent of the grains exhibited brownish cloudiness, which masked the birefringence and which was not removed by the nitric acid treatment.

The second relation appears to depend upon the tectonic history of the region. The three zircons from the Grenville subprovince in Ontario have uranium-lead ages which are in good agreement at 1000 *m y*. They include a range of crystal size from 200–350 mesh for the Tory Hill syenite to several millimeters for the Cardiff Uranium Mine sample. A number of other age determinations on uraninites and micas from this area also indicate an age of 1000 *m y*. On the other hand, three Precambrian zircons from the Cordilleran region of the western United States (Bagdad, Quartz Creek, and Pike's Peak) all give discordant uranium-lead ages. These results are in accord with the field observations that the Grenville in Ontario has been relatively undisturbed since Precambrian times, while the Cordilleran region has undergone recent orogenies. This regional effect should be examined further. For instance, it would be desirable to study zircon from Precambrian rocks in the Appalachian province, where discordant ages might be expected. The Capetown granite was buried under a mass of Devonian sediments which rest unconformably on it [*Nicolaysen*, 1954]. The cause of the discordant ages found for the zircon here may be connected with this history.

The extreme range of crystal size for the Ontario samples indicates that this property in itself is of minor importance in determining the quality of an age result. The U^{238}-Pb^{206} age for the syenite zircon indicates that crystals of minus 200-mesh size retained, on the average, more than 90 per cent of their lead over a time span of 1000 *m y*. This places a very low limit on the rate of diffusion of lead from the crystals, assuming no compensating losses of uranium by diffusion. When discordant ages do occur, it is possible that the degree of discordancy would be less for large crystals than for small ones, but no large crystals could be obtained from the formations which gave discordant ages in the present work. However, experience with such other minerals as monazite and columbite-tantalite has shown that samples with crystal sizes on the order of one cm will frequently give large age discordancies.

The appearance of the crystals under petrographic examination reveals nothing which can be correlated with age results. Cloudiness, zoning, and inclusions were about as common in samples which gave concordant ages as in those which gave discordant ages. Inspection of Tables 2 and 3 shows that there is no connection between the radiation damage to a zircon (indicated by the radiogenic lead content) and the agreement of the ages. Thus the present data suggest that the concordance or discordance of the ages obtained is a function of the post-crystallization history of the rock in which the zircon is found rather than some intrinsic property of the crystals themselves such as size, appearance, or amount of radiation damage. The degree of discordance of the ages is not a function of the ages of the zircons as can be seen by comparing the Capetown with the Quartz Creek or Bagdad results.

Mechanisms for age discordancies—Three types of age discordancies require explanation: (1) a Pb^{207}-Pb^{206} age which is higher than the age of the associated mica, (2) uranium-lead ages which are lower than the age of the associated micas, and (3) thorium-lead ages which are lower than the uranium-lead ages for the same zircons.

It is easy to imagine a mechanism which would account for the high Pb^{207}-Pb^{206} age at Quartz Creek. Since zircon appears to be more stable

than most of the minerals in a granite, it might be possible for zircons to be incorporated into a granite from some older source without losing all of their lead. If sufficient lead were retained, one or all of the uranium-lead ages would appear higher than the ages of such other minerals as micas which might have been completely reformed at the time of the formation of the granite. Some mechanism of this nature would seem to be the explanation at Quartz Creek where rubidium-strontium and potassium-argon measurements indicate the mica age to be about 1350 *m y*, but the zircon has a Pb^{207}-Pb^{206} age of 1700 *m y*. *Staatz* and *Trites* [1955, p. 8] mention the presence of inclusions of tonalite, quartzite, and hornblende gneiss in the outcrop from which granite 'A' was collected. In relatively recent times the U^{238}-Pb^{206}, U^{235}-Pb^{207}, and Th-Pb^{208} age values could have been lowered by some process such as lead loss, but the Pb^{207}-Pb^{206} age value remained high since it depends only on the Pb^{207}-Pb^{206} ratio of the lead in the zircon. In more extreme cases even the observed U^{238}-Pb^{206} age of a zircon might be greater than the age determined on associated micas. Future work will determine whether this type of discordance occurs frequently enough to be of importance.

An alternate, though unlikely, explanation of the high Pb^{207}-Pb^{206} age is radon leakage. The U^{235}-Pb^{207} age would be the true age if this were the sole cause of the age discordancy. This value for the Quartz Creek zircon is 1130 *m y*, which is less than the age of the mica in the granite, and is thus obviously low. Moreover, none of the remaining samples in Table 3 has a high Pb^{207}-Pb^{206} age. These considerations rule out radon leakage as playing any important role in the age discordancies found.

The more common type of discordance found in the present work is that for which the Pb^{207}-Pb^{206} age is equal to the potassium-argon and rubidium-strontium ages of the micas in the same rock, while the uranium-lead and thorium-lead ages are substantially lower. The mechanism whereby this could be accomplished is obscure. The results require that the zircons in a granite either lose lead or gain uranium and thorium, while at the same time the potassium-argon and rubidum-strontium ratios in neighboring micas are not affected. Certain evidence favors loss of lead as the cause of low ages. The pattern of the discordant ages, that is, Th^{232}-Pb^{208} < U^{238}-Pb^{206} < U^{235}-Pb^{207} < Pb^{207}-Pb^{206}, is independent of the thorium-uranium ratio and the uranium content of the zircons. The age pattern is about the same for the Capetown zircon, which has a thorium-uranium ratio of 0.166, as for the Pike's Peak zircon, with a thorium-uranium ratio of 1.15. That is, the Th^{232}-Pb^{208} age is 70 per cent of the U^{238}-Pb^{206} age at Capetown and 50 per cent of the U^{238}-Pb^{206} age at Pike's Peak in spite of the fact that the thorium-uranium ratios of the two zircons differ by a factor of seven. If parent addition is taken as the cause of the discordancies, a mechanism must be found by which the relative amounts of uranium and thorium added are determined to a considerable extent by the amounts of thorium and uranium in the zircons themselves. Also, if the true age of the zircons is known from the close agreement of the potassium-argon and rubidum-strontium ages of the micas, then it follows that the uranium-lead and thorium-lead ages are no lower percentage-wise for the Pike's Peak zircon than for the Capetown, Bagdad, and Quartz Creek zircons, which have three to ten times more uranium and about the same amounts of thorium. These observations make unlikely the addition of uranium and thorium from an outside source since the age patterns would then be expected to exhibit a much more erratic behavior over the wide range of uranium concentrations and the thorium-uranium ratios found in the zircons. Since the uranium and thorium concentrations in the individual minerals of the granites have not been determined except at Tory Hill, it is more difficult to exclude the possibility that uranium and thorium could have been added to the zircons from some mineral or minerals from within the granites.

Tilton [1956] reached the conclusion that lead loss is the more likely cause of low ages from a study of acid soluble lead from eight minerals with discordant ages, only one of which was zircon. It was found that minerals with high U^{238}-Pb^{206} and good Th-Pb^{208} ages contained a higher percentage of acid soluble radiogenic Pb^{206} and uranium than of radiogenic Pb^{208} and thorium. Other minerals with low Th^{232}-Pb^{208} and good uranium-lead ages contained higher percentages of soluble radiogenic Pb^{208} and thorium than of radiogenic Pb^{206} and uranium. From similarities between the uranium and thorium contents and the isotopic composition of the lead in the acid washes and the minerals it was concluded that the discordant ages resulted from losses of both parent and daughter from the samples and that

the ages were high if the loss of parent had predominated or low if the loss of daughter had predominated.

The fact that the zircons which have discordant ages are generally the ones which contain common lead is suggestive that other cations such as thorium and uranium might be added to the samples along with common lead, leading to a lowering of the uranium-lead and thorium-lead ages. The zircons which do not contain common lead would not have undergone this hypothetical addition and would then have concordant or nearly concordant ages. If the addition could take place at a low enough temperature, the micas might preserve their potassium-argon and rubidium-strontium ratios during the process. No petrographic evidence has been found which would support the addition hypothesis. None of the zircons exhibits the pyramidal growths noted by *Smithson* [1937] and *Poldervaart* and *Eckelmann* [1955] on zircons which have undergone presumed authigenic outgrowths or overgrowths. Occasional crystals could be found in most of the samples, except Ceylon and Natural Bridge, which had rounded cores of lower refractive index surrounded by more euhedral crystals of higher index. Often cracks radiated outward from the more metamict core due to differential expansion caused by the higher degree of radiation damage to the core. However, crystals of this type seemed to be too rare to explain large age discordancies such as at Pike's Peak. They were found with equal frequency in some samples, such as Redstone and Llano, which gave concordant or nearly concordant ages. It is felt that the arguments supporting lead loss have a more factual basis than those concerning uranium and thorium addition and that lead loss, or loss of uranium, thorium, and lead with loss of lead predominating, is the more probable cause of the low age values. It is difficult to imagine a process which will acount for the removal of lead from a zircon and which will not affect the mica age results. One experiment has been conducted to explore whether lead might be lost as a result of the annealing of a metamict zircon. Since lead apparently is not accommodated by the zircon lattice, it seems possible that it might be lost in the annealing process. Powdered Ceylon zircon was sealed in a silica-glass tube and held at 1000° C for two days. This treatment restored the crystal structure of the zircon to the undamaged state. The sample was removed from the silica tube and the powder and the inside of the tube were treated 15 minutes in cold 6M hydrochloric acid. Less than 1 μg of lead appeared in these washings from a sample which contained about 100 μg of lead. Then the zircon was dissolved and analyzed for lead. The unannealed zircon had previously been found to contain 115 ppm of Pb^{206}, as reported in Table 2. The annealed zircon had a Pb^{206} content of 112 ppm. These two results agree within the limits of analytical error and indicate that lead loss during the annealing process did not exceed two or three per cent and may have been entirely negligible. This result, however, does not exclude annealing as a mechanism for lead loss since the zircon was heated only two days and was out of its natural environment. Natural processes occurring over spans of millions of years might still involve losses of lead. A sample of Quartz Creek microlite was also annealed in the same manner as was the zircon. The starting material contained 0.91 pct lead and gave no lines on an x-ray powder diffraction pattern. The annealing completely restored the crystal structure without the loss of more than two per cent of the lead. This result may be of less significance than the zircon result since microlites appear to be able to incorporate more common lead than do zircons.

Very little is known concerning the mechanism by which the thorium-lead ages are lowered more than the uranium-lead ages for a zircon. One result has been reported by *Tilton* [1956] which bears on this problem. A powdered sample of the Tory Hill granite zircon was leached 15 minutes in hot 50 pct aqua regia, removing about 15 per cent of the lead. Isotopic analysis of the soluble lead showed that the acid treatment removed much more Pb^{208} than Pb^{206}. The starting material had a radiogenic Pb^{208} to radiogenic Pb^{206} ratio of 0.097, while the same ratio for the acid soluble lead was 0.706. In other words, radiogenic Pb^{208} in the sample is more susceptible to removal than is radiogenic Pb^{206} (and Pb^{207}). This effect is evidently connected in some way with the low thorium-lead age for the zircon. It might be due either to initial heterogeneous distribution of uranium and thorium in the mineral, with more thorium being located along fissures and grain boundaries, where the Pb^{208} can be removed with greater ease than can the Pb^{206} and Pb^{207}, or, less likely, to recent additions of thorium on the outside of the crystals or along fissures, where Pb^{208} would again be more easily removed.

The presence of common lead in the samples is

not explained by a lead-loss mechanism for age discordancies. If zircon loses lead, neighboring minerals are likely to lose lead also. They will release common lead into the environment of the zircon, some of which appears to end up strongly bound to the sample, although probably not in the zircon lattice itself.

Non-Isotopic Age Measurements

There are two ways to obtain a mineral age value which do not require an exact knowledge of the isotopic composition of the lead. The first, called the 'alpha-lead' method, yields an age from measurements of the total lead content of a mineral and its alpha activity, using the latter as an index of the combined uranium and thorium content, by assuming a thorium-uranium ratio typical of the mineral. The decay chains are also assumed to be in radioactive equilibrium. The other approach is the so-called 'chemical lead' method, which requires that the uranium, thorium, and lead contents of the sample be determined separately. In either of these cases it must be assumed that all of the lead contained in the mineral is of radiogenic origin.

The simplicity of these methods, which do not require a mass spectrometer, has created much interest in the possibility of their use in permitting a more rapid accumulation of age data. It is pertinent, therefore, to compare the isotopic ages presented in Table 3 with the non-isotopic ages which may be calculated from the analytical results shown in Table 2. This is done in Table 4 for both alpha-lead and chemical lead ages. The chemical lead values were determined by using the relations

$$t_1 = 7320\ \mathrm{Pb}/(\mathrm{U} + 0.322\ \mathrm{Th}) \qquad (1)$$

and

$$t = t_1 - k(t_1)^2 \qquad (2)$$

where t_1 is a first approximation to the age in millions of years; Pb, U, and Th are the concentrations in parts per million or other consistent units; t is a closer approximation to the age; and k is a constant which depends upon the ratio of thorium to uranium in the sample. The values of k were taken from the work of *Keevil* [1939].

The alpha-lead ages in Table 4 have been computed according to the following

$$t_1 = 2550\ \mathrm{Pb}/\alpha \qquad (3)$$

and

$$t = t_1 - 0.92 \times 10^{-4}(t_1)^2 \qquad (4)$$

where α = alpha disintegrations per mg-hour = (ppm U × 0.336) + (ppm Th × 0.0862), Pb is the lead concentration in parts per million and t_1 and t are again in millions of years.

The thorium-uranium ratios found for the zircon samples analyzed in this work range from 0.07 to 4.0, with an average of 0.23. This ratio gives a value of about 2550 for the constant in (3) and fixes the value of k in the second term of (4) at 0.92×10^{-4}.

In the second and fourth columns of Table 4 the figures in boldface type show the effect of correcting for the appreciable amounts of primary lead given in Table 3. These non-isotopic ages are lowered substantially by making this correction. It is evident that the two non-isotopic age methods give internally consistent results on either the uncorrected or the corrected basis, except for the Wichita Mountains samples, for which the differences would be eliminated by use of a constant representative of the actual thorium-uranium ratio instead of an average value.

Larsen and his co-workers at the U. S. Geological Survey have independently determined alpha-lead ages on zircons from several of the same localities, which are listed in Table 5. Their ages were computed according to (3), using a constant of 2400 and no further corrections. This corresponds to a thorium-uranium ratio of about 1.5

TABLE 4 – *Non-isotopic age comparisons for zircons*

Locality	Age in million years				
	Chemical lead	Corrected[a] chemical lead	Alpha-lead	Corrected[a] alpha-lead	Probable true age
Tory Hill, Ont., granite	930	**930**	920	**920**	1000
Cardiff Uranium Mine, Ont.	910	**910**	870	**870**	1000
Bagdad, Ariz.	680	**600**	675	**600**	1400
Quartz Creek, Colo.	1210	**930**	1170	**900**	1350
Pike's Peak, Colo.	610	**555**	620	**565**	1020
Llano, Texas	940	**940**	930	**930**	1100
Capetown, S. Africa	420	**330**	405	**320**	550–600
Wichita Mts., sample A	565	**515**	615	**560**	500–650
Wichita Mts., sample B	525	**505**	560	**540**	500–650
Ceylon	550	**550**	530	**530**	550
Redstone, N. H.	190	**190**	186	**186**	185

[a] These ages are corrected for the amounts of primary lead contained in the samples as given in Table 3.

TABLE 5 – *Comparison of alpha-lead age results*

Locality	Published age[a]	Recalculated age	This paper
	m y	*m y*	*m y*
Tory Hill, Ont., average of 4	990	960	920
Redstone, N. H., average of 4	235	247	186
Llano, Texas, average of 6	880	865	930
Wichita Mts., average of 13	635	635	550
Ceylon, average of 21	574	580	530

[a] Taken from H. Faul (ed.), *Nuclear geology*, John Wiley and Sons, Inc., 1954.

and neglects the exponential decay of the radioactive parents during the life of the mineral. The computed ages happen to be about the same whether the value of 2400 is used with no correction or 2550 is used with the correction term of (4). The results of the two types of calculation are given in Table 5 for samples which can be compared with ages obtained in the present work.

It is only when the non-isotopic age results are compared with the probable true ages in Table 4 that the weaknesses of the simpler methods become evident. The probable true ages are based on intercomparisons of uranium-lead, potassium-argon, and rubidium-strontium ages, except for the Ceylon sample, for which only uranium-lead results are available. Of the non-isotopic ages, a third to a half are lower than the probable true ages by more than ten per cent. Although there are hardly enough isotopic ages at present to allow a quantitative estimate of the risks involved in using non-isotopic ages by themselves, it is obvious that errors of as much as a factor of two do occur. Therefore, complete reliance of any single non-isotopic zircon age is unjustified and may lead to serious error. If a body such as a granite batholith is sampled extensively and found to give non-isotopic ages which agree throughout, then it is possible that this result represents the age. Further studies are necessary to determine whether age discordancies can be uniform in such a body or not. It is unfortunate that only single samples have been studied for granites which have discordant zircon ages. Regardless of the outcome of the problem concerning the errors in absolute age, the alpha-lead method should perform considerable valuable service to geochronology. For example, if alpha-lead ages for different samples from a granite batholith are variable, then it may be expected that the isotopic ages will be discordant by varying amounts. Areal surveys by the alpha-lead technique will undoubtedly reveal many places where interesting problems exist which may be investigated more thoroughly by isotopic studies.

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Gravity Cross Section of the Coast Range of Venezuela

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Abstract—The geologic mapping underway throughout the Caribbean province together with the seismic and gravity data becoming available suggested that a gravity profile across the Cordillera de la Costa of Venezuela might yield information of regional value. In August 1949, 44 stations were established from La Guaira to Ortiz. The resulting modified Bouguer anomaly values show a +45 mgal zone to the north of Caracas, an east-west trending 40 mgal negative zone between Caracas and San Juan de los Morros, passing upward to a −15 mgal zone to the south. The pattern is believed produced by a combination of normal thickening of the metasedimentary sequence, the presence of the thin edge of the granitic continental crust, and a slight regional downwarp not yet isostatically adjusted. The anomalies are discussed with reference to the local geology and the strong negative belt paralleling the West Indian island arc.

Introduction—The close association of large negative gravity anomalies with the arcuate type of island chain was first noted some years ago [*Vening Meinesz*, 1934]. The early idea postulating a large-scale downwarp of the Earth's crust parallel and peripheral to the island arc [*Hess*, 1938] appears to have received the most subsequent favor, with much of the more recent geophysical and geologic work yielding evidence tending to corroborate such a view.

The Antilles island group from Cuba on the northwest, through Haiti and the Dominican Republic, Puerto Rico, and the Virgin Islands, and south through the Leewards and Windwards to Trinidad and the South American continent represents one of these arcuate belts. The gravity work at sea as done by Vening Meinesz, Wright, Hess, Brown, Ewing, Hoskinson, Worzel, and others demonstrates the presence of the anomaly belt. Isostatic negative anomalies between 50 and 100 mgal occur along the north coast of eastern Cuba; a 100 to 150 mgal zone borders the northern shores of Hispaniola and Puerto Rico; and values in excess of −150 mgals accompany the island string southward, apparently dying out just to the north of Trinidad. Another east-west trending belt picks up just to the north of Aruba, Curacao, and Bonaire and contains negative anomalies between 100 and 150 mgal. The axes of these zones are shown on the inset map of Figure 1.

The correspondence of the cessation of the southern end of the strong negative anomaly belt, as measured in the sea stations, to the immediate north of the South American continent as indicated in Figure 1 with the eastern terminus of the metamorphic complexes of the North Range of Trinidad and the Cordillera de la Costa of Venezuela suggests the possibility that this continuous mountain chain represents a portion of the Caribbean arc in which the causal forces have subsided, and that a study of such an exposed area might permit the examination of a previously depressed zone. The recentness of much of the fault movement as noted in the course of geologic mapping in the Caracas area indicated the possibility that although this mountainous region was presently undergoing uplift, some remnant of a former large anomaly not yet isostatically adjusted may still be in evidence.

Procedure—A reconnaissance gravity survey involving the establishment of 44 stations was conducted from August 5 to August 9, 1949 in the portion of the Venezuelan Cordillera indicated by Figure 1, a cross section of the 65 km width of the metamorphic range from the north coast to the unmetamorphosed sediments of the Orinoco Basin thereby being obtained. The principal facts for the resulting stations are included in Table 1.

The gravimeter used was the special high range (5500 mgal) geodetic-type Worden instrument (no. 10c) previously described by *Woollard* [1950]. The features of this meter include built-in temperature compensation, a drift of approximately one mgal per hour, and a reading sensitivity of 0.1 mgal. This particular instrument was in South America at this time as part of the program of world gravity measurements undertaken by Woods Hole Oceanographic Institution and the University of Wisconsin.

Sixty-one observations were made in a closed loop from a base station established in the basement of the Cartografía Nacional building in Caracas in order to determine the gravity characteristics of the locations chosen. The major loop

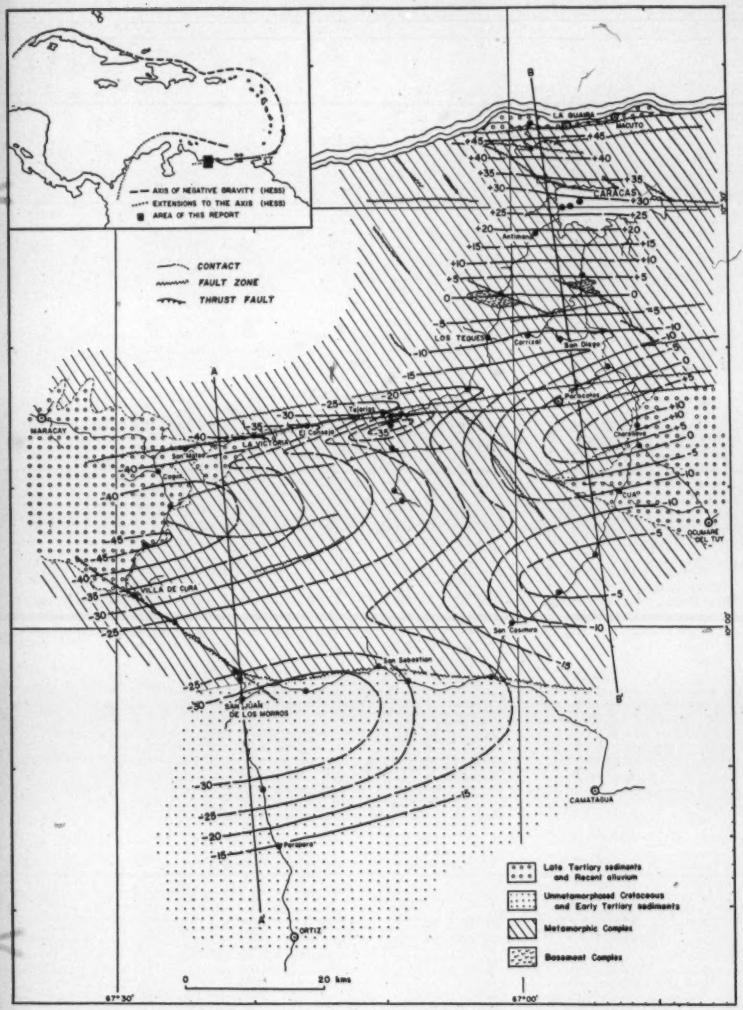

FIG. 1 – Isogam map of the Caracas region; inset shows regional trend of the negative gravity axes

TABLE 1 – *Principal facts for the Venezuelan gravity stations*

Station	Latitude (North)		Longitude (West)		Elevation	Observed gravity	Sea level gravity	Elevation and mass correction	Theoretical gravity	Bouguer Anomaly	Terrain correction	Modified Bouguer anomaly
	°	′	°	′	m					mgal		mgal
Caracas, Cartografía Nacional, basement floor	10	30.6	66	55.8	910.7	978.0687	978.2204	−0.1793	978.0411	+27.6	2.0	+29.6
Caracas, Observatorio	10	30.4	66	56.5	1045[a]	978.0399	978.2204	−0.2057	978.0147	+25.2	4.7	+29.9
Caracas, Loma Quintana, BM T1x67 (1946)	10	30.4	66	57.0	1077.5	978.0311	978.2204	−0.2122	978.0082	+22.9	4.7	+27.6
Antimano, plaza, BM D-46(1941)	10	28.0	66	58.8	935.8	978.0500	978.2190	−0.1842	978.0348	+15.2	4.3	+19.5
A, Sebastopol, South end of bridge	10	24.1	66	01.6	1075[a]	977.9977	978.2168	−0.2116	978.0052	−7.5	8.1	+0.6
Los Teques, plaza, BM 13(1947)	10	21.2	67	02.6	1167.7	977.9762	978.2154	−0.2299	977.9855	−9.3	1.1	−8.2
B, Boqueron, road intersection	10	17.1	67	04.1	1004[a]	977.9914	978.2132	−0.1976	978.0156	−24.2	5.9	−18.3
C, Guayas River, West end of bridge	10	15.3	67	08.8	474[a]	978.0923	978.2122	−0.0933	978.1189	−26.6	4.0	−22.6
D, Loma de Hierro, ridge crest	10	09.1	67	09.2	1121[a]	977.9569	978.2090	−0.2207	977.9883	−31.4	3.3	−28.1
E, Tiarito, road intersection	10	09.1	67	09.0	1246[a]	977.9341	978.2093	−0.2453	977.9640	−29.9	2.0	−27.9
F, Stream crossing	10	12.7	67	09.6	850[a]	978.0179	978.2108	−0.1673	978.0435	−25.6	2.4	−23.2
G, Ridge crest	10	13.7	67	09.3	873[a]	977.9947	978.2115	−0.1718	978.0397	−45.3	3.2	−42.1
H, Road intersection	10	15.3	67	09.5	490[a]	978.0896	978.2122	−0.0964	978.1158	−26.2	3.5	−22.7
Las Tejerias, plaza, BM A64(1942)	10	15.4	67	10.2	499.2	978.0847	978.2123	−0.0982	978.1141	−29.4	3.6	−25.8
El Consejo, plaza, BM A67(1942)	10	14.4	67	15.7	552.8	978.0681	978.2118	−0.1089	978.1029	−34.8	3.1	−31.7
La Victoria, plaza, BM A68(1942)	10	13.6	67	19.6	558.0	978.0612	978.2133	−0.1098	978.1015	−40.3	1.7	−38.6
San Mateo, plaza, BM A71(1942)	10	12.9	67	24.8	493.1	978.0678	978.2104	−0.0970	978.1134	−45.6	0.9	−44.7
Cagua, plaza, BM A26(1943)	10	11.2	67	26.9	534.0	978.0678	978.2101	−0.1051	978.1050	−37.2	0	−37.2
Casupito, road intersection BM A121JL-(1946)	10	08.9	67	26.1	452.9	978.0757	978.2089	−0.0892	978.1197	−44.0	1.3	−42.7
Cagua, Villa de Cura road, BM A120JL-(1946)	10	06.2	67	27.8	451.9	978.0713	978.2075	−0.0890	978.1185	−47.2	1.2	−46.0
Villa de Cura, plaza, BM A118JL(1946)	10	02.3	67	28.5	527.2	978.0664	978.2055	−0.1037	978.1018	−35.4	0.6[b]	−34.8
I, La Garita River, east end of bridge	10	00.1	67	25.7	474[a]	978.0861	978.2043	−0.0933	978.1110	−23.9	0.8[b]	−24.1
J, Guarico River crossing, south end of bridge	9	57.3	67	21.4	433[a]	978.0924	978.2029	−0.0852	978.1177	−25.3	0.7[b]	−24.6
San Juan de Los Morros, Plaza, BM G113JL(1946)	9	54.7	67	21.0	428.3	978.0838	978.2016	−0.0842	978.1174	−33.6	0.5[b]	−33.1
K, La Puerta, monument arch	9	56.9	67	21.1	418[a]	978.0913	978.2027	−0.0823	978.1204	−29.1	0.6[b]	−28.5
L, Parapara, road intersection	9	44.2	67	18.1	219[a]	978.1382	978.1962	−0.0431	978.1531	−14.9	0	−14.9
M, Stream Crossing, north end of bridge	9	47.8	67	19.3	269[a]	978.1155	978.1981	−0.0530	978.1451	−29.6	0	−29.6
N, Guarico river crossing, west end of bridge	9	55.3	67	16.0	368[a]	978.0953	978.2019	−0.0724	978.1295	−34.2	0.4[b]	−33.8
San Sebastian, plaza, BM A108JL(1946)	9	57.0	67	10.7	368.1	978.1020	978.2028	−0.0724	978.1304	−28.4	0.5[b]	−27.9
O, Suata river crossing, east end of bridge	9	56.4	67	05.8	357[a]	978.1071	978.2024	−0.0703	978.1321	−25.0	0.4[b]	−24.6
San Sebastian—San Casimiro-Camatagua road junction, BM A104JL(1946)	9	56.3	67	02.7	391.3	978.0996	978.2024	−0.0770	978.1254	−25.8	3.7[b]	−22.1
San Casimiro, plaza, BM A102JL(1946)	10	00.2	67	01.1	477.8	978.0967	978.2043	−0.0941	978.1102	−13.5	0.6[b]	−12.9
El Loro, BM E100JL(1945)	10	02.5	66	57.7	666.7	978.0664	978.2056	−0.1313	978.0743	−7.9	3.9[b]	−4.0
El Pelon, BM E98JL(1945)	10	05.6	66	55.2	414.2	978.1165	978.2047	−0.0815	978.1232	−6.7	2.7[b]	−4.0
Cua, plaza, BM E96JL(1945)	10	09.7	66	53.4	243.8	978.1510	978.2093	−0.0480	978.1613	−10.3	0	−10.3
P, Cua—Ocumare—Charallave road junction	10	13.3	66	51.7	285[a]	978.1564	978.2106	−0.0561	978.1545	+1.9	0.5	+2.4
Q, Charallave, plaza	10	15.2	66	51.9	333[a]	978.1578	978.2122	−0.0655	978.1467	+11.1	1.2	+12.3
R, Paracotos—Charallave—El Valle road junction	10	18.4	66	54.0	782[a]	978.0495	978.2139	−0.1539	978.0600	−10.5	4.3	−6.2
S, San Diego—Charallave—El Valle road junction	10	21.3	66	54.4	1223[a]	977.9626	978.2154	−0.2407	977.9747	−12.1	2.6	−9.5
Carrizal, plaza	10	21.1	66	59.6	1260[a]	977.9503	978.2153	−0.2498	977.9655	−15.2	4.3	−10.9
U, San Diego, Plaza	10	20.8	66	57.3	1268[a]	977.9485	978.2151	−0.2496	977.9655	−17.0	4.1	−12.9
V, Las Lechosas, culvert	10	25.4	66	55.7	920[a]	978.0415	978.2176	−0.1811	978.0365	+5.0	2.7	+7.7
W, El Copey, road intersection	10	34.7	66	59.2	564[a]	978.1475	978.2226	−0.1110	978.1116	+35.9	8.4	+44.3
Airport, Pan American baggage room	10	36.2	66	59.3	84[a]	978.2490	978.2234	−0.0165	978.2069	+42.3	3.8	+46.1

[a] Barometric elevation.
[b] Approximate terrain correction.

was in turn made up of a series of smaller circuits to enable instrument and elevation drift control. Where possible the stations were located on established bench marks along the major highways and in the central plazas of the municipalities. The identification numbers of these bench marks are included in Table 1. Where bench marks were lacking the stations were taken at prominent

buildings, bridges, and road intersections to provide ease of reoccupation. Alphabetic designations have been applied to stations located intermediate to population centers. An attempt was made to establish a station at least every five kilometers when directly crossing the strike of the rocks, with longer separations permitted while paralleling the strike. The average station separation along the circuit line is approximately seven kilometers.

Latitudes and longitudes of the stations were obtained by location on topographic base maps. The northern portion has topographic coverage at a scale of 1:25,000, with 1:100,000 maps available for the entire area. The coordinates of bench mark stations were further checked by location listings supplied by Cartografía Nacional. It is believed that all of the resulting latitude values are consistent with an accuracy of 0.1 mgal.

The elevations of the stations were determined either from the bench marks or by barometric means. The more exact bench mark elevations were obtained from a station listing as supplied by Cartografía Nacional, and are considered to be within 0.1 m. The barometric values are believed accurate to two meters, representing an error not greater than 0.6 mgal in their use.

A density of 2.67 was used throughout in the elevation and mass and terrain correction calculations, and appeared consistent with the various rock types occurring in the region. The 1:25,000 topographic maps available for the northern part of the area permitted accurate terrain corrections to be made here. The corrections for areas not having this detailed coverage were based on the 1:100,000 map series augmented by triangulation of the topography surrounding the stations. Cases where only inexact terrain corrections were of necessity made are designated on Table 1. The rugged topography of portions of the area did not permit the use of the standard correction tables in several cases, in which the cylindrical shell formulas were necessarily applied.

The values for the sea level gravity were obtained from the tables of *Lambert* and *Darling* [1931]. The observed gravity was based on the 980.1190 gal value as determined by Woollard, Black, and Bonini (unpublished manuscript, World gravity measurements, 1952–1954, 1954). This same point was previously occupied in 1947 by G. R. Shelton of the U. S. Coast and Geodetic Survey with the following results:

Observed gravity	980.118 gals
Free-air anomaly	0.126
Bouguer anomaly	0.030
Indirect anomaly (D = 96 km)	0.041 [a]
D = 56.9 km	0.060 [a]
D = 96 km	0.039 [a]
D = 113.7 km	0.032 [a]

[a] Isostatic (Pratt-Hayford).

The difference in the observed gravity figures for this station as obtained by the gravimeter and the U. S. Coast and Geodetic Survey pendulum is consistent with comparable differences noted elsewhere in the world, and may be attributed to several factors entering into the pendulum calculations. In more recent stations where these factors have been recognized and taken into account the two methods no longer show such a difference. For this reason the Worden figure has been used as a basis for the observed gravity computations.

In summary, the accurate elevation values and detailed topographic coverage available in the northern part of the area produced relatively reliable modified Bouguer anomaly results in these stations. Many of the southern locations lacked both an exact elevation and a detailed topographic map, with a consequent loss in accuracy. Consideration of all of the introduced errors suggests that the final figures are within three milligals, sufficient to establish the general gravity configuration for the region.

Geology of the area—The general geology of the region covered by the present gravity investigation was initially considered by *Aguerrevere* and *Zuloaga* [1937], with more detailed work having subsequently been done by *Dengo* [1953], *Smith* [1953], *Shagam* [1955], and MacLachlan (in progress).

The area essentially consists of the four major rock units indicated in Figure 1; a basement of possible Precambrian age, a broad band of metasedimentary and meta-igneous rocks of probable Cretaceous age, the unmetamorphosed Cretaceous and Tertiary section in the basin to the south, and local covers of undifferentiated late Tertiary sediments and Quaternary alluvium.

The Sebastopol basement crops out in the two small areas shown between Los Teques and Caracas. Although now gneissic, evidence suggests it was a coarse-grained granite at the time of deposition of the unconformably overlying Caracas group sediments.

The metamorphic complexes make up the major portion of the mountainous area of the Venezuelan Cordillera, reaching from the northern coastline to the Orinoco Basin. These rocks may be divided into two groups, based both on relative age and subsequent degree of metamorphism. The older complex, the Caracas group, is largely found in

the northern portion of the metamorphic area and is composed chiefly of sediments apparently deposited by an early Cretaceous sea transgressing on the stable platform. The arkoses, conglomerates, orthoquartzites, dolomitic and reefal limestones, and calcareous and non-calcareous shales were subsequently metamorphosed to the amphibolite facies, producing the microcline-dolomite rocks and the schists and marbles of the Las Brisas formation, the Antimano limestone, and the Las Mercedes formation, imparting a well-defined schistosity and lineation in the process. Amphibolite layers interbedded in the sequence presumably are metamorphosed basaltic flows. The most recent work of *Shagam* [1955] indicates that the thick sequence of metamorphosed volcanic rocks making up the Villa de Cura group [*Aguerrevere and Zuloaga*, 1938] overlies the Caracas group. The metamorphic rocks are intruded by serpentinized peridotite and hornblende diorite masses with related dikes of soda granite. Shagam also shows that the series of basalts, tuffs, and gabbroic dikes and sills making up the Tiara volcanic sequence were erupted after the metamorphism of the Caracas and Villa de Cura groups, and in turn were exposed and supplying detritus by Coniacian time.

The younger metamorphic complex collectively known as the Paracotos formation occurs mainly in the southern portion of the metamorphic belt and overlies unconformably the older metamorphic rocks. This mixture of graywackes, conglomerates, and cherts, locally interbedded with tuffaceous and limy layers is believed to represent sediments rapidly deposited under eugeosynclinal conditions during latest Cretaceous time. Metamorphism shortly after deposition converted these sediments chiefly to very low grade phyllites and metagraywackes. In neither this nor the earlier metamorphism did a thick cover of sediments appear to be present.

The southern margin of the metamorphic area is bounded by a series of unmetamorphosed Cretaceous and early Tertiary sediments. These are strongly folded and thrust southward between Ortiz and San Juan de los Morros. The youngest rocks in the region are the local covers of late Tertiary clastics and Quaternary alluvium as found in the Lake Valencia basin, the Tuy valley, and along the northern coastline.

The entire region structurally lies on the southern limb of a major east-west anticlinorium, with all magnitudes of folding from many miles across to the microscopic fold lineation. Prominent transcurrent shear zones cross the area in a N80°E direction, accompanied by N60°W normal faulting. Southward thrusting occurs in the southern portion of the area and northward thrusting is found to the north.

Geophysical interpretation—The spacing of the gravity stations taken allowed the contouring of the modified Bouguer anomalies into the isogam map of Figure 1. A high area of more than +45 mgal trends east-west across the northern part of the region, with the anomaly regularly decreasing southward to a −45 mgal zone in the central portion, increasing again to a −15 to the south. The positive zone to the north occurs associated with rocks of the older Caracas group, with the two upfaulted areas of basement not appearing to have markedly influenced the regularly decreasing pattern. The low zone in the west-central portion of the region is found over the Villa de Cura group and younger rocks. The overall regular pattern is locally upset by several minor highs, presumably representative of varying depth to basement.

The picture as presented here conforms with similar patterns as established elsewhere, in that gravity highs are usually associated with structural highs. The overall position of the major anticlinorium is therefore reflected in the general gravity pattern. The smaller scale folding does not appear to have influenced the picture. The extensive faulting locally produces slightly positive domes representative of lesser depth to basement, and slightly negative areas occur in conjunction with the larger transcurrent shears. The areas of exposed intrusive rocks do not appear to have altered the overall gravity pattern. Stations made adjacent to the large Loma de Hierro ultrabasic intrusive show a negligible effect. The density variation of the near surface rocks is believed insufficent to account for the broad changes in gravity.

Two representative gravity profiles constructed along A-A′ and B-B′ are presented in Figure 2, indicating the existence of a broad gravity low having a width approximating 60 km and negative values in excess of 40 mgals. The +30 anomaly in the vicinity of Caracas suggests that the high northern coastal block is not compensated and thus has no root. The various positive trending zones presumably result from the vertical component of movement of separate fault blocks along the transcurrent shears. The decreasing magni-

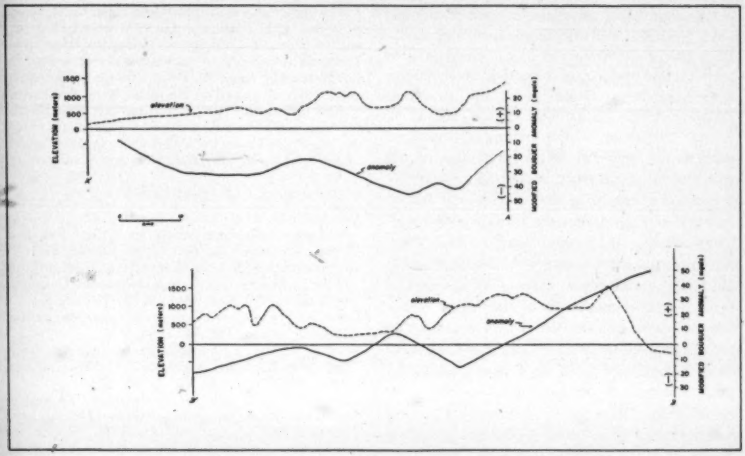

FIG. 2 – Gravity and topographic profiles along A-A′ and B-B′

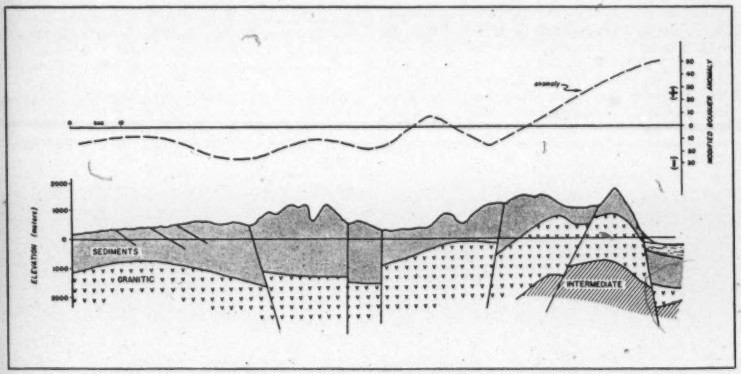

FIG. 3 – Composite gravity profile along a diagrammatic structural cross section

tude of the negative anomaly at the southern margin of the area suggests both that the granitic layer is still not overly thick at this distance from the continental margin, and that the overlying sedimentary and meta-sedimentary cover thins southward at right angles to an east-west axis passing slightly to the south of San Juan de los Morros. Topographic profiles are included to demonstrate the lack of correspondence between elevation and the nature and size of the anomaly. A composite gravity profile accompanying a diagrammatic structural cross-section is shown in Figure 3. The thickening of the metamorphic sequence in the central portion of the section and the influence of differential fault movement on the gravity profile are indicated.

Consideration of the geological and geophysical data presently available on this southern Caribbean—northern South American marginal area permits the drawing of several general conclusions. The negative gravity of the land portions probably results from a combination of normal thickening of the meta-sedimentary sequence, the presence of the thin edge of the granitic continental crust, and a slight downwarping not yet adjusted. The gravity and bathymetric data suggest that the granitic layer terminates at about the present margin of the Venezuelan coastline and does not thicken appreciably southward in the region covered by the present survey. It also appears as if the higher mountainous portions of the Venezuelan cordillera do not have a thick granitic root, placing the Mohorovicic discontinuity at a level considerably less than the 30 to 35 km figure accepted for continental areas. Although the presence of a granitic basement rock is indicated by surface geological studies, it should be noted that such a layer need not be present to account for the gravity pattern.

Acknowledgments—This investigation was carried out for the Instituto Nacional de Minería y Geología of the Ministerio de Fomento of the Venezuelan government. In addition to bearing a part of the expenses involved, the Instituto and its Director, A. Schwarck Anglade, are thanked for furnishing base maps, aerial photographs, and transportation. The Cartografía Nacional division of the Departamento de Obras Públicas was also of much assistance in matters of tation elevation and location.

The survey was made possible through the generous efforts of H. H. Hess and G. P. Woollard that permitted Norman Harding to defer departure from Venezuela sufficiently to enable the circuit across the Cordillera to be made. Hess was of much guidance and aid through all phases of the work. P. A. Rogers was of help in some of the problems encountered in the reducing operations. A portion of the expenses for this work was borne by a Office of Naval Research contract (N6onr-27008) with Princeton University.

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Report of the Committee on Runoff, 1955–1956

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During the year 1955–1956 the Committee on Runoff conducted several informal discussions by correspondence on subjects of runoff from small watersheds and of flood and drought studies. Owing to the limitation in space for publication, voluminous material involved in the discussiong cannot be all published. This report presents some highlights developed from discussions on runoff studies of small watersheds. The report constitutes neither recommendations nor complete opinions on the part of the Committee members, but simply reflects some fragmental thoughts that have been expressed during the discussions. The Committee members hope that this report will serve as seeds to bring forth further discussions from the readers and thus to fulfill the aim to stimulate research, secure coordination, and facilitate dissemination of information in runoff studies of small watersheds.

ON RUNOFF FROM SMALL WATERSHEDS

The small watershed and its characteristics—From the hydrologic point of view, a distinct characteristic of the small watershed is that the effect of overland flow rather than the effect of channel flow is a dominating factor affecting the peak runoff. Consequently, a small watershed is very sensitive to high-intensity rainfalls of short durations, and to land use. On larger watersheds, the effect of channel flow or the basin storage effect becomes very pronounced so that such sensitivities are greatly suppressed. Therefore, a small watershed may be defined as one that is so small that its sensitivities to high-intensity rainfalls of short durations and to land use are not suppressed by the channel-storage characteristics. By this definition, the size of a small watershed may be found from few acres to 1000 acres, or even up to 50 sq mi. The upper limit of the area depends on the condition at which the above-mentioned sensitivities become practically lost due to the channel-storage effect.

On a small watershed, the effect on peak runoff is dominated by the overland flow. When the watershed becomes large, this effect of overland flow is gradually replaced by that of channel flow. This phenomenon is demonstrated by a current study by W. D. Potter. (The result of this study was presented in a paper entitled "Relations between low and high frequency peak rates of runoff" at the 38th Annual Meeting of the Union in Washington, D. C., April 29, 1957.)

The effect of land use—As mentioned above the small watershed is sensitive to land use, and hence the effect of land use plays an important role in the hydrology of small watersheds. Several major discussions on this subject were brought up as follows: On small agricultural watersheds, land use has been shown to be a significant factor affecting peak runoffs, particularly where one kind of land use covers the entire watershed [*Potter*, 1950]. On larger watersheds the effect of channel storage does not cause differences in peak runoff because of land use. This has been shown by studies that there was no significant correlation of peak runoff with land use in the larger watersheds in the Allegheny-Cumberland Plateau [*Potter*, 1954]. Based on the analysis of the peak-runoff data obtained by the Soil Conservation Service from experimental watersheds in Maryland, Ohio, Wisconsin, and Nebraska [*Potter*, 1950], it can be shown that for areas under consideration the land use factor may become insignificant for sizes greater than probably 1000 acres.

A current study on the effect of vegetative cover on runoff from snall agricultural watershed was reported by N. E. Minshall (unpublished paper presented at the Annual Meeting of the American Society of Agricultural Engineers in Chicago, Illinois on December 17, 1951, "Effect of conservation practices on watershed yields"). In this study the effect of vegetative cover on runoff from a particular area was determined by plotting the mass runoff from that area with that from another. This is commonly referred to as double mass plotting. If the amounts on both areas have been accurately measured, any deviation from a reasonably straight line can be attributed to a change in cropping practices, provided the watersheds are close enough to each other so that there has been no great differ-

ence in total rainfall and that the cover on one of the areas has been reasonably constant during the period of record. Such a plotting for the Edwardsville Watersheds W-1 and W-2 is shown in Fig. 1. Watershed W-1 (27 ac) was two-thirds or more cultivated during most of the period of records, but the cover was 100 pct alfalfa during the period of 1941–44. Watershed W-2 (50 ac) was from 90 to 100 pct pasture during the entire period of record. The plotting shows that W-1 in 100 pct alfalfa had only 0.73 as much runoff as W-2, but as a cultivated area W-1 had slightly more runoff than W-2. This indicates a reduction in total runoff of about 30 pct for a complete cover change on the 27-ac area. Breaking down the double mass plotting into two seasons as shown in Figures 2 and 3 indicates that the reduction in amount of runoff affected by this extreme change in vegetative cover was largely during the period from May to October and that cover made little difference in runoff during the winter. This lack of cover influence during the winter is due more to the surface soil having a high moisture content from lack of transpiration of plants than to the presence of a frost layer.

The per cent reduction during storms of considerable magnitude can be expected to be less than in those of small storms. Because of the difference in rainfall amounts it is not practical to analyse the cover effect for individual storms by plotting total runoff of each storm on W-1 against runoff on W-2 and computing the line which best fits these points by the method of least squares. To eliminate this variation in rainfall between two areas the amount retained from the excess portion of the storm can be compared as suggested by Minshall (in his unpublished paper of 1951). From such a comparison, two equations are obtained for W-1; one for 96 pct cultivated and the other for 100 pct alfalfa.

$$Y = P_1 - R_1 \quad \text{and} \quad X = P_2 - R_2$$

P_1 and P_2 are excessive precipitations in inches for the two watersheds, and R_1 and R_2 are its corresponding runoffs in inches. Thus for 100 pct alfalfa cover on W-1, $P_1 - R_1 = 0.09 + 0.966\ (P_2 - R_2)$ or $R_1 = P_1 + 0.966\ R_2 - 0.966\ P_2 - 0.09$. Using these equations the runoff on W-1 for all storms for both cover conditions can be computed by substituting the known values of P_1, P_2, and R_2, and solving for R_1. The values thus obtained for each storm were plotted against each other and the equation of the line determined by least squares. From the line thus determined the

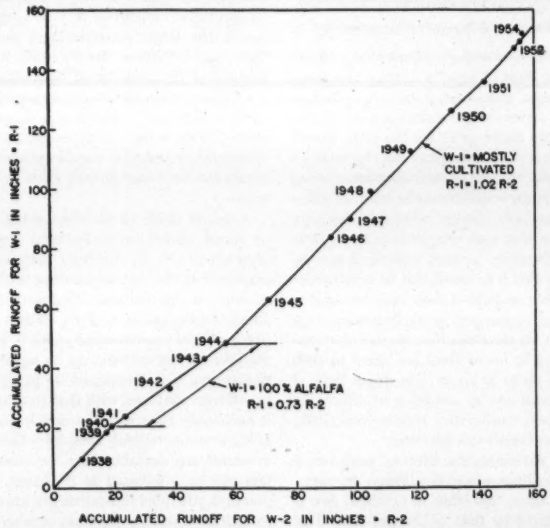

FIG. 1 – Double mass plotting for annual runoff from Watersheds W-1 and W-2, Edwardsville, Ill.

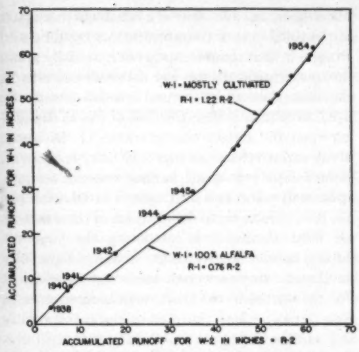

FIG. 2 – Double mass plotting for May-October runoff from Watersheds W-1 and W-2, Edwardsville, Ill.

per cent reduction in total runoff per storm for storms of various magnitudes was computed and is shown on the graph of Figure 4A. This graph shows that for a storm having an estimated recurrence of once in 25 years, one can expect only 7.5 pct reduction in total runoff for the complete cover change from 96 pct cultivated to 100 pct alfalfa. Examination of the runoff records shows that 50 pct of the runoff during the entire period occurred in storms having less than 0.75 inch of runoff. For these storms the per cent reduction in total runoff for the complete cover change is at least 16 pct.

Similar comparisons were made to determine the effect of cover changes on peak rates of runoff. In this analysis retention rates were used in place of total retention. This method was first used by *Baird* [1946]. The retention rate is considered as the maximum rainfall intensity for the time of concentration of the watershed, minus the peak rate of runoff. The results in Figure 4B and 4C show a 9 pct reduction in rate of runoff for a storm occurring once in 25 years for the cover change from 96 pct cultivated to 100 pct alfalfa. Over two-thirds of the storms had peak rates of runoff less than one inch per hour and for these the reduction in peak rate would be more than 22 pct.

On small urban watersheds, as pointed out by G. R. Shanklin, the natural characteristics of the runoff and concentration factors are both materially altered by the development. Changes in land use may increase the runoff factor by as much

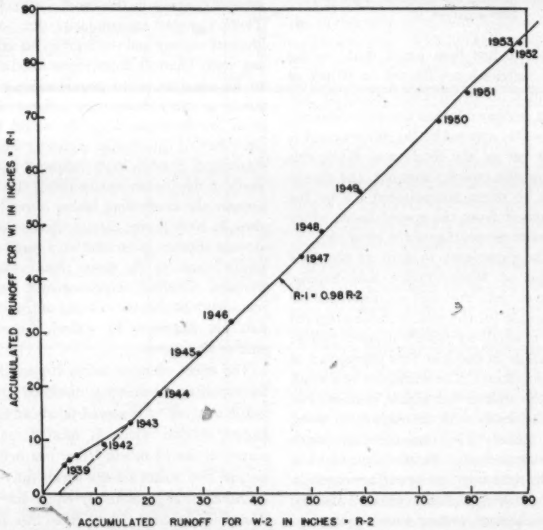

FIG. 3 – Double mass plotting for November-April runoff from Watersheds W-1 and W-2, Edwardsville, Ill.

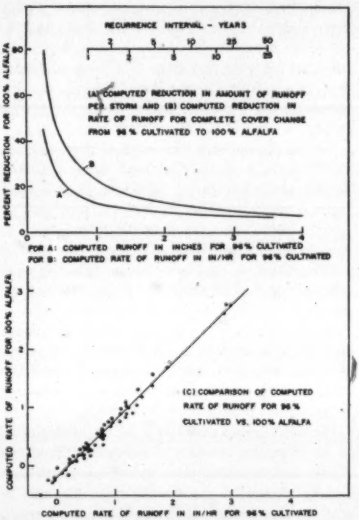
RECURRENCE INTERVAL - YEARS
2 5 10 25 50
1 2 5 10 25
(A) COMPUTED REDUCTION IN AMOUNT OF RUNOFF PER STORM AND (B) COMPUTED REDUCTION IN RATE OF RUNOFF FOR COMPLETE COVER CHANGE FROM 96 % CULTIVATED TO 100 % ALFALFA
PERCENT REDUCTION FOR 100 % ALFALFA
FOR A: COMPUTED RUNOFF IN INCHES FOR 96 % CULTIVATED
FOR B: COMPUTED RATE OF RUNOFF IN IN./HR FOR 96 % CULTIVATED
(C) COMPARISON OF COMPUTED RATE OF RUNOFF FOR 96 % CULTIVATED VS. 100 % ALFALFA
COMPUTED RATE OF RUNOFF FOR 100 % ALFALFA
COMPUTED RATE OF RUNOFF IN IN./HR FOR 96 % CULTIVATED

FIG. 4 – Effect of land use on runoff from W-1, Edwardsville, Ill.

as 100 pct but it has been found that, on the average, such increases are limited to 50 pct or less. In residential areas, especially where the size of lots has been increased by new zoning ordinances, the impervious area created by the development is only 10 to 15 pct of the total area. While this change increases the runoff somewhat, the change is believed to be often compensated for by the reduction in runoff from the graded lawns which comprise a greater percentage of the total area.

Based on the experience to date at the New Jersey Division of Water Policy and Supply, Shanklin believes that the most significant factor which is responsible for the great increase observed in flood-peaks of small watersheds in metropolitan areas is the change in the inlet time component of the concentration factor. The sensitivity of a small watershed to the shorter but higher intensities of rainfall varies inversely with the magnitude of the concentration factor. The concentration factor consists of two components; the inlet time which is a measure of the time required for surface runoff to concentrate in the nearest stream channel and the travel time or channel routing time required to reach the point of measurement. For the larger watersheds, the inlet time is a relatively small part of the total time of concentration or lag time and changes in that component do not materially affect the concentration factor. For the small watersheds, the inlet time under natural conditions may be equal to or greater than the time of travel, depending upon the surface characteristics of the basin. Many surface characteristics such as type of cover, surface slope, type of soil, surface retention storage, apparently affect this inlet time. The Division has not been able as yet to define which of these factors are most significant in producing the large reduction in inlet time which the studies of some fully developed, storm-sewered areas have indicated. For the northern, red shale, metropolitan area in New Jersey, where the ground surface is rolling and surface slopes are somewhat steep, unit hydrograph and other studies have confirmed that inlet times average five to ten minutes for fully developed, storm-sewered areas. In the southern metropolitan area, however, which is located on the coastal plain with relatively flat surface slopes, the surface characteristics have not apparently been changed sufficiently by development to produce any appreciable reduction in the inlet time.

The development of small watersheds also creates changes in the time of travel component. These changes are primarily due to the loss of channel storage and the increase in velocity resulting from channel improvements which have had to be constructed to provide larger channel capacity to carry the increase volume of flood runoff from the developed area. As would be expected, the effect of this change increases with the size of watershed. Studies have indicated that for watersheds of five to ten square miles, this change may become the controlling factor instead of the inlet time. In New Jersey, the net effect of loss of channel storage appears to be relatively small owing to the limited size of the flood plain along its small streams. Channel improvements, on the other hand, may double the velocity of travel when channels are improved in walled, paved flumes or similar structures.

The effect of storm-sewer suppression on small metropolitan streams was disclosed by unit hydrograph analysis of observed floods at the Irvington gaging station which is located on the headwaters of the Elizabeth River just below the junction of two storm sewers which fully enclose two branches of approximately equal size and length. The drainage area tributary to this station is 2.9 sq mi of fully developed urban area in the cities

of East Orange and Newark. Figure 5 shows the effect of storm sewer suppression on the peak discharge rates and time-lags at the Irvington station. It is to be noted that the surface storage in streets which was required to provide these suppressions did not create sufficient flooding to warrant any demand for the enlargement of this sewer system. In the light of this analysis, consideration is now given in the estimates of design floods of ungaged areas for some degree of storm sewer suppression. The effect of this suppression is greatest for the smaller drainage areas where the duration of the critical storm is 60 min or less. The effect disappears as the drainage area increases and the critical average storm intensity is reduced by reason of its depth-area relation. For the Elizabeth River, this point approximates five square miles.

As reported by A. J. Cooper, a problem on small-watershed research work of the Tennessee Valley Authority is the selection of an equation to define the interrelationship of hydrologic factors governing runoff, peak discharge, and sediment load. One of the purposes is to detect the difference, if any, in the hydrologic characteristics of a watershed due to cover or land-use changes. The analytical method was described [*Cooper* and *Snyder*, 1956] showing the evaluation of the effect of changes with time of cover density and land use upon sediment load characteristics of two tributary streams in the Tennessee Valley.

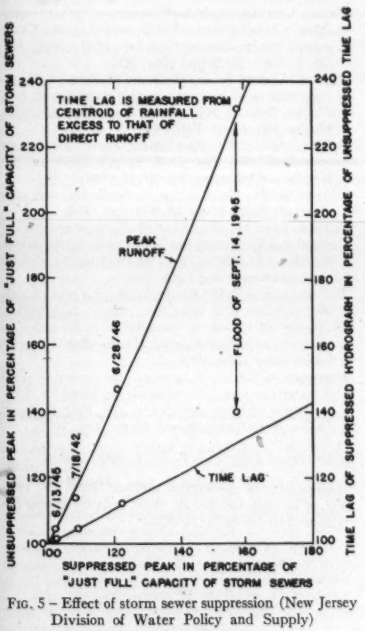

FIG. 5 – Effect of storm sewer suppression (New Jersey Division of Water Policy and Supply)

In each case, an empirical mathematical expression was established, one having linear coefficients and the other capable of being resolved logarithmically into an equation of linear coefficients. The justification of the empirical relations was based upon a combination of theoretical principles and upon intuitive deductions. The regression coefficients were determined by fitting the equation to the data by the method of least squares, and the significance of a time-regression function to represent the effect of changing cover was judged by an analysis of variance. The complete regression equation in each case included all those important hydrologic variables which are known to have significant effect upon the production of storm sediment loads and, in addition, a time-regression function.

One form of the regression equation which was used in the analysis is based upon the premise that the occurrence of a hydrologic event of certain magnitude is the result of the interaction of several causative factors. Expressed mathematically, the magnitude of the event is equated to the product of the magnitudes of the several causative factors. In this form, the equation must be transformed to the logarithmic form for the solution of the coefficients by the method of least squares. In the other form, not requiring logarithmic transformation, the magnitude of the hydrologic event is equated to a summation of terms which are each the products of closely related causative factors.

Hydrologic studies of small watersheds—Various phases on hydrologic studies of small watersheds were discussed by the Committee members and the results may be summarized as follows.

The significance of hydrologic studies of small watersheds is apparent from the growing need for the discharge potential of small drainage areas that arises in connection with the design of (1) cross-drainage works for the protection of highways, railroads, and canals, (2) drainage structures on agricultural lands, and (3) storm-sewer system in urban or metropolitan areas. Furthermore, there is a need for better understanding of the hydrology of small watershed which is necessary in order to

treat water on the land as a natural resource susceptible of management.

Current methods for estimating peak runoff from small watersheds are:

(1) Empirical or semi-empirical methods developed from experience and judgment, involving the use of rules of thumb and empirical formulas, curves, and tables. A recent study at the *University of Illinois* [1953, 1955] resulted in a collection of 107 formulas in current use. It also reveals that 25 state highway departments are using the Talbot formula either directly or supplementally for design purposes.

(2) Statistical analysis of flood records on regional basis, involving probable flood frequency and drainage basin characteristics which are applied through a family of index curves to areas which involve no appreciable change in natural runoff characteristics. This method has been used widely for large watersheds for which data are available. For small watersheds the use of the method is handicapped by the deficiency of data.

(3) Rational method, the use of which is not generally recommended as *Potter* [1950] has pointed out that the assumptions involved in this method cannot be established satisfactorily by either actual data or logical reasoning. G. R. Shanklin, however, indicated that the smaller the watershed, the more direct is the relation between rainfall intensity and flood peak discharge, and consequently, the rational method may be applied to watersheds of two square miles or less in urban areas.

(4) Synthetic flood hydrographs based on the application of unitgraphs to design storm patterns including flood routing where required for larger watersheds. Unitgraph analysis has been used by *Chow* [1952] for a typical urban watershed. B. S. Barnes indicated that many attempts have been made to adapt the unitgraph procedure to cross-drainage problems but except in a few instances, they have been unsuccessful. Since most of the channels are not well defined, the changing conditions of cover, tillage, and litter during the season make the short lag time a highly variable quantity. A unit rain in so small a basin must be so brief that only a thundershower will serve. The channels, being normally dry, will lose enough water into cracks, drills, and burrows and by absorption into the root zone to obscure the true shape of so short a hydrograph. Usually the drainage system is too poorly developed to be comparable with that of a gaged basin for which good unitgraph data are available, and from which a suitable unitgraph might otherwise be obtained. These obstacles can and will be surmounted, but it will probably require more data than are generally available at the present time.

(5) Correlation analysis for developing formulas or charts showing the effect on peak runoff by various hydrologic factors such as rainfall intensities, land use and slope, frequency of occurrence, and watershed dimensions. Two outstanding methods of this kind are the summation method developed by the U. S. Soil Conservation Service [*Sutton*, 1943] and the new method by the *Bureau of Public Roads* [1951].

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Reviews, Abstracts, and Bibliography

Reviews and Abstracts

Abstracts of the papers presented at the Thirty-Eighth Annual Meeting, Washington, D. C., April 29–May 2, 1957 listed in the order of the last name of the first author

L. T. ALDRICH (Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, D. C.) *The Measurement and Applications of Mineral Ages* Modern measurements of radioactive ages of rocks using the decay of U-Pb, Th-Pb, Rb-Sr, and K-A have shown that the latter two usually give accurate absolute ages on micas from granites and pegmatites. The ubiquitous occurrence of mica extends the number of sedimentary formations whose ages can be bracketed by common igneous rock. The possibilities for measurements of the age of minerals in these formations are hopeful.

Measurements made while testing the Rb-Sr and K-A methods have already shown conclusively that geologic formations older than 2500 m y exist in North America, South Africa, and Australia. It has also been found that at least 11 Precambrian granites and pegmatites in western United States have values for their ages close to 1350 m y, indicating widespread formation of rocks at that time.

R. A. ALLEN, J. O. ELLIS, AND J. M. SASSMAN (Office of Meteorological Research, U. S. Weather Bureau, Washington, D. C.) *Some Uses of Prognostic Charts in Weather Forecasting* The use of prognostic charts in local weather forecasting is discussed, with particular reference to the division of effort between the centralized prognosis of large-scale sea-level and upper-air flow patterns, thickness, and vertical motion, and the localized forecasting of weather elements. Experiments have been conducted in the objective use of prognostic charts for forecasting temperature and precipitation. The results of these experiments are described, including analysis of the relative error in the prognostic chart and error in the interpretation of the prog in terms of weather.

ALLEN M. ALPER AND ARIE POLDERVAART (Department of Geology, Columbia University, New York 27, N. Y.) *Zircons from the Animas Stock and Associated Rocks, New Mexico* Zircons have been studied by measurement of lengths and widths of 200 crystals for each sample. Data are analyzed by the reduced major-axis method. Eleven samples from the Animas stock, emplaced at shallow depth, have zircons with like reduced major axes. A sample from an apophysis and one from a roof protruberance have somewhat different zircon reduced major axes. Contrasting bands in fine- and coarse-grained layered units have zircons with like reduced major axes. The size of zircons varies considerably throughout the stock. Results are compared with those obtained for the Bald Mountain batholith, Oregon, which is emplaced at moderate depth. Four samples of tuff which originated from the site of the stock, and two samples from a related nearby vent have zircons with reduced major axes like those of the Animas stock. Three granitic xenoliths and a younger extrusive have different zircon reduced major axes. Five different granitic intrusives also have zircons with different reduced major axes. It is concluded that zircons may be used to characterize granitic rocks of igneous origin and to distinguish derivatives of one magma from those of older or younger magmas, even if the rocks are of identical chemical and mineralogical composition.

J. K. ANGELL (Office of Meteorological Research, U. S. Weather Bureau, Washington, D. C.) *Lagrangian Wind Fluctuations at 300 mb as Obtained from Transosonde Flights* The contribution of periods ranging from eight to 96 hours to the variance of the horizontal velocity components and ageostrophic velocity components is determined from transosonde flights of at least two days' duration. The contribution of these periods to the meridional flux of momentum is estimated. The evidence for inertial oscillations is considered.

H. BAADSGAARD, A. O. C. NIER, AND S. S. GOLDICH (University of Minnesota, Minneapolis, Minn.) *Investigations in A^{40}/K^{40} Dating* In connection with the Minnesota program of A^{40}/K^{40} dating in the Lake Superior region, a number of samples have been dated which previously have been investigated in other laboratories by the A^{40}/K^{40}, Rb^{87}/Sr^{87}, and U/Pb methods. Results obtained at Minnesota are shown below.

Location	Mineral	K[a]	A^{40}/K^{40}	Age × 10^{-9} yr
		pct		
Dickinson County	Microcline	9.78	0.0942	1.21
Mich.		9.80	0.0937	1.20
			0.0955	1.22
			0.0946	1.21
Spruce Pine Dis-	Muscovite	8.47	0.0225	0.366
trict, N. C.		8.43	0.0211	0.345
			0.0223	0.363
San Diego (Pala),	Lepidolite	8.42	0.00574	0.100
Calif.				
Bikita S. Rh.,	Lepidolite	7.30	0.278	2.44
Africa		7.37	0.274	2.43
Portland, Conn.	Lepidolite	8.70	0.0153	0.256
		8.71		
Cardiff Twp.,	Biotite	7.42	0.0776	1.04
Canada				

[a] Average K-values used in calculations $\lambda_e = 5.57 \times 10^{-11}$/yr, $\lambda_\beta = 4.72 \times 10^{-10}$/yr.

A mass spectrometer of high sensitivity with a gas recirculation system permits the quantitative measurement of 10^{-6} cc STP of A^{40}. A small mineral sample (one to two grams) insures complete decomposition in NaOH, and a pyrophoric uranium getter enables pure gas samples to be obtained. Determinations on cogenetic mica-feldspar pairs from granite and granite gneiss show a relatively constant argon deficiency factor for feldspars compared to micas; pegmatitic pairs show greater variability.

J. R. BALSLEY AND A. F. BUDDINGTON (U. S. Geological Survey, Washington, D. C.) *Remanent Magnetism of the Russell Belt of Gneisses, Northwest Adirondack Mountains, New York* A previous study of the magnetic properties and chemical and mineralogic composition of the iron-titanium oxides of several hundred specimens of metamorphic rocks from the Adirondack Mountains has shown that the rocks containing magnetite as the predominant accessory mineral have essentially 'normal' magnetization (north-seeking pole down), and rocks containing members of the ilmenite-hematite series as the predominant accessory mineral have essentially 'reversed' remanent magnetization (north-seeking pole up). Runcorn has suggested that the rocks containing magnetite and having a lower coercivity have lost an earlier reverse remanent magnetization still retained by the more highly coercive rocks containing mixtures of ilmenite and hematite. A subsequent study of 128 samples from a single belt of rocks with the same thermal history has shown that in rocks in which magnetite is the predominant accessory mineral the magnetization is normal and the directions are concentrated at approximately 56° from the present field. This condition indicates stable magnetization of an essentially isotropic medium. In rocks that contain members of the ilmenite-hematite series as the predominant accessory mineral the remanent magnetization is reversed and the directions are randomly scattered except that they are rare in the sector opposite to the one in which the axes of rocks containing magnetite are concentrated. This condition indicates a property of magnetic self-rotation in the grains of ilmeno-hematite possibly related to their crystallographic orientation. This ability to become magnetized in a direction essentially opposite to an applied field can be produced by exsolution structures within the grains, as previously suggested by the authors and others, or by disorder structures as proposed by Verhoogen.

MORTON L. BARAD (Atmospheric Analysis Laboratory, Geophysics Research Directorate, Air Force Cambridge Research Center, Bedford, Mass.) *A Background History of Project Prairie Grass* During the summer of 1956, three university teams and three Air Force teams participated in a field program at O'Neill, Nebr. One of the objectives of the program was to determine the rate of diffusion of a tracer gas as a function of meteorological parameters. This paper includes a brief history of research in the field of diffusion and indicates how this history affected the planning and operation of the Prairie Grass program. This background information serves as a general introduction to the technical papers on Prairie Grass to be presented at this session.

F. B. BARKER (U. S. Geological Survey, Denver, Colo.) AND R. C. SCOTT (U. S. Geological Survey, Boise, Idaho) *Uranium and Radium on Ground Waters of the Llano Estacado, Texas and New Mexico* Water samples were collected from 48 wells and springs in the Ogallala formation in the Llano Estacado, or southern High Plains, of Texas and New Mexico. The Ogallala, a fluviatile deposit, is hydrologically and geologically isolated in this region; therefore, the observed radiochemical concentrations are considered as inherent characteristics of the formation in this area. The uranium concentrations ranged from 0.9 to 46 parts per billion (median 6.3 ppb), and the radium concentrations ranged from <0.1 to 1.4 micromicrocuries per liter (median 0.1$\mu\mu$c/1). The uranium concentrations show a tendency to correlate with the gross chemical character of the waters in accordance with the expected chemical behavior of uranium. The departure of the radium-uranium ratios in all samples from radioactive equilibrium value is explained on the basis of carbonate-complexing of uranium and selective adsorption of radium by minerals having a capacity for base exchange.

GEORGE L. BATE AND J. R. HUIZENGA (Argonne National Laboratory, Lemont, Ill.) *Determination of Thorium in Meteorites by Neutron Activation* Analysis of several stone meteorites yielded thorium concentrations ranging from 0.1 to 0.001 p.p.m., with an accuracy of two to three per cent. The larger thorium contents were found in chondrites while the lowest concentrations occurred in an achondrite and in the olivine phase of a pallasite. The thorium content of a terrestrial dunite was approximately intermediate to the range of meteoritic concentrations. Radiochemical assay was based upon the 310-kev gamma activity of the Pa^{232} daughter of Th^{232} produced by neutron activation of Th^{232}, using a thorium standard as a flux monitor and Pa^{231} tracer to determine the chemical yield. The advantages of the method are (1) thorium contamination introduced during the chemical separations does not affect the results, and (2) a high sensitivity is obtained, which with the neutron flux available in the Argonne CP-5 reactor, approaches 10^{-4} p.p.m. Further, gamma-ray analysis affords greater selectivity of the Pa^{233} activity from possible extraneous activity remaining after chemical purification than does the gross β^- assay method. Since for geochemical reasons the dunite should represent the low side of terrestrial thorium concentrations, the method described is also appropriate for analysis of terrestrial rocks of all types.

CHARLES C. BATES (Office of the Development Coordinator, Office of Naval Research, Washington 25, D. C.) *Recruitment and Salary Problems in the Oceanographic Profession as of Late 1956* Results are reported concerning a salary and employment survey made of the oceanographic profession by the U. S. Navy Hydrographic Office in mid-September 1956. Students now studying oceanography are inadequate in number to fill vacancies caused by attrition in the profession, much less to permit expansion. Salaries were not competitive with those paid at all levels of experience to other scientists in the basic fields of physical and engineering sciences. Steps being taken by the U. S. Navy

to alleviate this personnel shortage and salary deficiency are discussed.

SIEGFRIED J. BAUER (Signal Corps Engineering Laboratories, Fort Monmouth, N. J.) *A Possible Troposhere-Ionosphere Relationship* A relationship between characteristics of the ionospheric F_2-layer and the passage of cold fronts in the troposphere is shown to exist by using the superposed epoch method. The change in virtual height of the F_2-layer associated with the passage of cold fronts is proved to be statistically significant. The results of our study are also investigated with respect to a hypothesis based on the concept of dynamic coupling between lower and upper atmosphere, and are found to be consistent with such a concept as well as with earlier reported correlations between meteorological and ionospheric variables.

EARL S. BELOTE (U. S. Coast and Geodetic Survey, 641 Washington St., New York 14, N. Y.) *The Geodesic Line*—This paper is a report of investigations leading to the development of a precise and direct solution of the inverse position computation over lines which may occur in surveys made by Hiran or EPI; that is, up to approximately 650 mi. The first phase of this investigation deals with the basic integrals of the problem and the development of the integrals of Helmert's classic solutions, with all coefficients in their hypergeometric form. The second phase is the development of the formulas dealing with characteristics of the right triangle corresponding to the one used in the present computation of geodetic positions. The third phase is the comparison of the solution of this triangle, with a corresponding triangle computed on a sphere of a chosen radius, which in turn leads to the precise solution.

ALFRED K. BLACKADAR AND KAJIT BUAJITTI (Pennsylvania State University, University Park, Pa.) *Diurnal Wind-Structure Variations in the Planetary Boundary Layer* Averages of the wind vector at four times of the day are shown for 29 days during the summer of 1951 at Wichita and Oklahoma City. The periodic portion of the variation is an ellipse at all levels, with the major axis more or less in the direction of the wind speed. The largest amplitude occurs at about 2500 ft above the ground. The equations of motion are solved with the aid of an electronic analogue computer for the case where the eddy viscosity is distributed arbitrarily in height and sinusoidally in time. It is concluded that variations of the type which were observed can occur only if both the average value and the amplitude of the variation of the eddy viscosity decrease rapidly with height in the middle portion of the boundary layer.

PAUL BOCK AND JOHN C. GEYER (Johns Hopkins University, Baltimore, Md.) *The Determination of Quantity of Storm-Water Flow on Small Urban Areas* A new method for determining quantity of storm-water flow on small urban areas is based upon three years of rainfall-runoff measurements on areas ranging in size from a fraction of an acre (inlet areas) to 150 acres (small urban areas). The method consists of three parts: (1) determining the flow to each inlet based upon a five-minute rainfall intensity, (2) attenuating the flow peak from each sub-area (group of inlets) as it moves down the pipe, using Schrank's equation, and (3) summing each inlet hydrograph to determine the total hydrograph at the design point. Using this method, computed peaks agree closely with measured peaks, while the rational method gives poor results. The limits of applicability regarding size and different types of surfaces have not been determined, although the analyses are still in progress. The work was performed at the Johns Hopkins University, Institute of Cooperative Research, Storm Drainage Research Project, and is sponsored by Baltimore City, Baltimore County, and the Maryland State Roads Commission.

ROSCOE R. BRAHAM, JR. (Department of Meteorology, University of Chicago, Chicago, Ill.) *Precipitation Processes as Revealed by First Radar Echoes—Arizona 1955* For the past two years, the Institute of Atmospheric Physics, University of Arizona, has used a TPS-10 radar to make extensive measurements of radar returns from cumulus clouds in the vicinity of Tucson. The radar data from ten days in the summer of 1955 have been analyzed with a view toward establishing the level of first formation of precipitation, day-to-day variation, average dimensions of first echo, average duration, and fraction reaching ground.

H. R. BRANNON, JR., A. C. DAUGHTRY, D. PERRY, W. W. WHITAKER, AND M. WILLIAMS (Humble Oil and Refining Co., Houston, Texas) *Radiocarbon Evidence on the Dilution of Atmospheric and Oceanic Carbon by Carbon from Fossil Fuels* The dilution of atmospheric carbon dioxide by carbon dioxide from fossil fuels is estimated to be about 3½ pct, on the basis of radiocarbon assays of tree rings of known ages from several trees of different genera, after allowance has been made for effects attributable to ecological differences. The cumulative mass of fossil carbon dioxide released to the atmosphere is 3.3×10^{17} gms, equivalent to about 14 pct of the carbon dioxide in the atmosphere. Based on these data, the fractional part of the atmospheric carbon dioxide which enters the ocean each year is estimated to be 0.062. Radiocarbon assays of several nineteenth-century marine shells and of their modern counterparts indicate a one to two per cent dilution of shallow oceanic carbonates by carbon dioxide from fossil fuels. Use of these data in a simplified mathematical model of atmosphere-ocean yields information on mixing times of the ocean.

C. L. BRETSCHNEIDER (Beach Erosion Board, Washington 25, D. C.) *Joint Distribution of Wave Heights and Lengths* Wave records were analyzed to determine the joint distribution relationship between wave heights and wave lengths. Records used were obtained from (1) Fort Peck Reservoir, Montana, (2) Lake Texoma, Texas, (3) Lake Okeechobee, Florida, and (4) the Gulf of Mexico. Also used were the Pacific Coast wave records from R. R. Putz (Statistical Distribution of Ocean Waves, *Trans. Amer. Geophys. Union*, v. 33, pp. 685–692, 1952).

In all cases, distribution of both the relative heights ($\eta = H/\bar{H}$) and also the relative lengths ($\lambda = T^2/\bar{T}^2$) take on essentially the gamma-type distribution for

heights as given by Putz or approximately the Rayleigh-type distribution given by Longuet-Higgins (On the Statistical Distribution of Heights of Sea Waves, *J. Mar. Res.*, pp. 245–266, 1952). In fact, one finds the accumulative distributions to be very nearly

$$P[\eta] = 1 - e^{-\eta^2/\overline{\eta^2}} \tag{1}$$

and

$$P[\lambda] = 1 - e^{-\lambda^2/\overline{\lambda^2}} \tag{2}$$

where η^2 and λ^2 are the averages of the sums of squares of η and λ, respectively. $P[\eta]$ gives the per cent of waves $\leq\eta$ and $P[\lambda]$ gives the per cent of waves $\leq\lambda$.

Wave records analyzed give correlation coefficients r between η and $\lambda \pm 0.40$, depending on the type of wave record and method of analysis used. For the data analyzed the following serves as a very good prediction formula for the joint accumulative distribution between H and T^2

$$P[\eta, \lambda] = 1 - e^{-\eta^2/\overline{\eta^2}} - e^{-\lambda^2/\overline{\lambda^2}} + e^{-\frac{1}{1-r^2}\left[\frac{\eta^2}{\overline{\eta^2}} - \frac{2r\eta\lambda}{\sqrt{\overline{\eta^2}\,\overline{\lambda^2}}} + \frac{\lambda^2}{\overline{\lambda^2}}\right]} \tag{3}$$

WALLACE S. BROECKER (Lamont Geological Observatory, Columbia University, Palisades, N. Y.) *Variations in the C^{14}/C^{12} Ratio of Atlantic Ocean Surface Water* A series of measurements in surface water samples obtained from the Atlantic Ocean and its adjacent seas are useful not only in that they provide the necessary control values for C^{14} studies on deep water samples, but also for the information they furnish regarding deep ocean circulation. A total of 16 surface ocean water samples have been measured with a precision of better than one per cent.

The surface water of the South Atlantic Ocean appears to have a two per cent lower C^{14}/C^{12} ratio than that in the North Atlantic. It will be shown that such a difference would be expected if the net northward surface transport of six million cubic meters per second is balanced by net southward flow through the North Atlantic Deep Water system. Many measurements on the North Atlantic Deep Water show it to have a uniform C^{14}/C^{12} ratio about seven per cent lower than that of North Atlantic surface water. The C^{14}/C^{12} values in surface waters in the Caribbean Sea add support to this hypothesis. Since the Caribbean water is a mixture of both North and South Atlantic surface water it should have C^{14}/C^{12} ratios intermediate between the two. The average of seven such samples falls 0.7 pct below that of the North Atlantic Surface Water.

WALLACE S. BROECKER, ROBERT D. GERARD, AND BRUCE C. HEEZEN (Lamont Geological Observatory, Columbia University, Palisades, N. Y.) *Deep Water Circulation in the Atlantic Ocean* A total of 35 radiocarbon measurements have been made on subsurface samples taken from the Atlantic Ocean and its adjacent seas with a precision greater than one per cent. The C^{14}/C^{12} ratios from 19 samples of North Atlantic Deep Water average 6.5 pct lower than North Atlantic Surface Water. Using equilibrium assumptions this corresponds to an age of about 550 years. There is no significant trend with either latitude (from 40° N to 4° S) or with depth (2800 to 5000 m). It thus appears that the rate of mixing within the mass exceeds the rate of net southward transport.

Samples from the lower salinity masses immediately above and below the North Atlantic Deep Water in the equatorial region have significantly lower C^{14}/C^{12} ratios. Whether this is due to an older age or a low source water value is not clear. A limited number of measurements on bottom samples in the Caribbean and adjacent Atlantic indicate that the C^{14}/C^{12} ratio in the Venezuela Basin is two per cent lower than that in Cayman Sea which in turn is two per cent lower than the water in the Atlantic at the estimated sill depth for these basins. The data support the hypothesis that the water in both basins is supplied through the Windward Passage.

HARRISON BROWN AND CHARLES R. MCKINNEY (Division of Geological Sciences, California Institute of Technology, Pasadena, Calif.) *The Existence of Specific Groups of Chondritic Meteorites* X-ray fluorescence has been applied to a study of the distribution of chromium, manganese, iron, cobalt, and nickel in stony meteorites. The results confirm that chondrites can be divided into specific groups which differ appreciably from each other in composition. We have found that the concentrations of cobalt and nickel are particularly sensitive indices for the classification of chondrites as the concentrations of both elements vary over a large range, yet are remarkably constant for the meteorites of a given group. By contrast, the concentration of manganese in chondrites of all groups is nearly constant. There are at least three major groups of chondrites (excluding the carbonaceous and enstatitic varieties) characterized by the following approximate weight ratios of cobalt, nickel, and iron to manganese.

	Co/Mn	*Ni/Mn*	*Fe/Mn*
Group I	0.19	4.1	81
Group II	0.13	3.1	69
Group III	0.08	2.1	61

The weight ratio of chromium to manganese was found to be about 1.1 in all groups. Comparison of these results with those of Urey and Craig (*Geochimica et Cosmochimica Acta*, v. 4, pp. 36–82, 1953) indicate that their 'high iron' group corresponds to our Group I, while their 'low iron' group is actually a mixture of two groups which have nearly the same total iron content.

ARTHUR H. BROWNLOW (Department of Geology and Geophysics, Massachusetts Institute of Technology, Cambridge, Mass.) *The Oxygen Isotope Thermometer: A Critical Review* The general method and theoretical basis of the oxygen isotope thermometer, developed by Urey and Epstein and applied by numerous of their students, are discussed in detail with emphasis on the necessary basic assumptions. Use of spectral data and methods of calculation are outlined. Calculations indicate that the range of variation of spectral data and of calculated isotopic frequency shifts will not significantly affect the results of the thermometer. However, the latter may be significant in other applications of isotopic variability. Use of

the thermometer is evaluated by a consideration of the following possible variables: (1) variation of the isotopic composition of the oceans, (2) non-equilibrium deposition, (3) record preservation, (4) biologic variables, and (5) application procedure. In particular, the possible effects of the natural occurrence of two different forms of calcium carbonate is discussed. It is concluded that the thermometer is of qualitative use only.

F. CHAYES (Geophysical Laboratory, Carnegie Institution of Washington, Washington 8, D. C.) *The δ_α Spacing in Intermediate Plagioclase* Using the data of P. Gay it is shown that δ_α varies with composition as the reciprocal of the average run length of the major constituent in a two-element random run sequence containing NαA's and NβB's, where α is the proportion of tetrahedral sites occupied by Al. The case corresponds to virtually complete short-range Al-Si disorder in at least one direction.

EDWIN J. CHERNOSKY (Ionospheric Physics Laboratory, Geophysics Research Directorate, Air Force Cambridge Research Center, Bedford, Mass.) *Magnetic Disturbance: A Principal or a Secondary Solar Geomagnetic Effect* Magnetic disturbance D is generally attributed to irregular above-normal solar emissions, and magnetic quiet S_q to their absence. As magnetic quiet also occurs during active Sun epochs, the question is advanced: Can magnetic quiet also result from non-fluctuating above-normal emissions (for example, S_{qe})? A simple Earth-Sun-beam geometry to provide an affirmative solution requires a wide angle (>45°) conical beam of enhanced steady emission (*u-v*, x-ray, and/or others) originating at a sunspot or active area. A fringe (>5°) of varying emission encompasses this beam which can have a tail of (slower) particles. The passage of a diameter of this idealized beam across the Earth provides for a short magnetic disturbance followed by a few days of magnetic quiet and then a magnetic storm, a type of sequence noted by Bartels. The magnetic storm results, as an after effect, from the breakdown of an undetermined terrestrial condition built up during the enhanced steady radiation period, from the fluctuating fringe effects and from particle re-entry and influx. The variable time 'delay' between flares and storms results from the independence between flare occurrence and beam fringe passage across the Earth. Sudden 'commencements' indicate the end of the buildup from the enhanced steady beam impingement giving the Forbush-Vestine S_q-SC amplitude relationship. More frequent interference between fluctuating and non-fluctuating emissions of neighboring spots (with consequent diminution of terrestrial effects) decreases the 27-day recurrence tendency at sunspot cycle maximum.

FRANK CHEW (Marine Laboratory, University of Miami, Coral Gables, Fla.) *The Hydrography of the Florida Gulf Coast Water* Six hydrographic cruises, totaling more than 1000 hydrographic stations, were made in the waters over the continental shelf off the Florida Gulf Coast. The results of two cruises are presented. It is shown that a highly saline tongue, originating in Florida Bay, is sandwiched in between the brackish inshore water and a less saline tongue farther offshore. The circulation pattern is discussed, in part to show that the Apalachicola River discharge is the origin of the offshore less saline tongue and in part to show that the salinity pattern, and hence probably water motion, are essentially the same through depth.

WAN-CHENG CHIU (Department of Meteorology and Oceanography, New York University, New York, N. Y.) *The Observed Mean Monthly Wind Fields in the Lower Stratosphere and Upper Troposphere over North America* The mean monthly wind fields at five different levels from the 300-mb surface to the 30-mb surface were constructed from rawinsonde data taken by stations in North America and adjacent waters over the four-year period, 1951–1954. These wind fields are represented by streamlines and isotachs on isobaric maps. The general and detailed features of these fields are discussed.

ALLAN COX (Department of Geology, University of California, Berkeley, Calif.) *Remanent Magnetization of an Eocene Formation from Oregon* The remanent magnetization of the lower to middle Eocene Siletz River Volcanic Series of northwestern Oregon indicates that the early Tertiary magnetic field may have been significantly different from the present one. Eight flows within 20 miles of location 44° 50′ N and 123° 35′ W have an average direction of magnetization of north 70° east and 55° down, with a circle of confidence at the 95 pct level of 7°. Three of the flows are antiparallel to the remaining five. Reduction of scatter on correcting for geologic tilt suggests magnetic stability. Scatter in the direction of magnetization of samples from a single flow was strikingly reduced by heating samples and cooling them in a field-free space.

H. E. CRAMER (Massachusetts Institute of Technology, Round Hill Field Station, South Dartmouth, Mass.) *Organization and Objectives of MIT's Field Experiments during Project Prairie Grass* Organization of personnel and equipment for carrying out the combined diffusion-meteorological field experiments is described. Objectives and techniques of data analysis are discussed.

HAROLD L. CRUTCHER (National Weather Records Center, U. S. Weather Bureau, Asheville, N. C.) *Cyclone Distributions along the East Coast of Asia as Characterized by the Bivariate Normal Distribution* In many scientific fields, the bivariate normal distribution has been used to characterize the distribution of observed data. These data have been in the form of paired observations or of elements which were broken down into paired orthogonal components. The distribution of 24-hour displacements along the east coast of Asia has been given by Mantis and Miller in 1946 in their study of extra-tropical cyclogenesis in the Pacific coastal region of Asia. As an extension of this study and of a paper presented at the 150th meeting of the AMS in New York, this paper shows that the distribution of Asiatic cyclones may also be depicted by the bivariate distribution. In the case of Asiatic cyclones, the distributions, for the period reported

by Mantis and Miller, must be considered to be elliptical rather than circular. This is in contrast to the circularity pattern exhibited by the cyclone patterns of the east coast of the United States.

ROBERTS C. CURTIS (Department of Meteorology, Pennsylvania State University, University Park, Pa.) *Large-Scale Vertical Motion, Stability, and Thunderstorm Occurrence in July 1955* The results of a study of the frequency of occurrence of thunderstorms as related to the large-scale vertical motion and static stability are presented. Two measures of stability are used, the Showalter index and a modification of it which includes the mean mixing ratio of the 850–500-mb layer. Vertical motion is found to be an important factor influencing the occurrence of nocturnal thunderstorms. The modified stability index is a better predictor of the occurrence of thunderstorms than the Showalter index.

PAUL E. DAMON AND J. LAURENCE KULP (Lamont Geological Observatory, Columbia University, Palisades, N. Y.) *Alpha-Helium Ages of Pegmatite Zircons* Alpha-helium ages of a number of pegmatite zircons have been measured by isotope dilution and alpha scintillation counter technique. The following ages were obtained: four Ontario zircons, 670–880 m y; two Ceylon, 500–550 m y; one Henderson Co., N. C. 220 m y; Oklahoma (fresh), 365 m y; Oklahoma (metamict), 90 m y. The metamict Oklahoma zircon which has very low retentivity has received about the same total alpha irradiation as Ceylon zircon which has high retentivity. Measured alpha activity is in agreement with previous work, but the helium content measured by isotope dilution is somewhat higher than for previous volumetric measurements.

GEORGE T. DELLERT, JR. (Office of Meteorological Research, U. S. Weather Bureau, Washington, D. C.) *An Experiment in the Mesoanalysis of Upper-Air Data* A set of detailed mesoscale upper-air charts are analyzed for the weather situation of May 25–26, 1955, using the sea-level mesomaps of the Texas-Oklahoma research network as a base and applying derived thickness patterns to obtain contour patterns aloft. Techniques for evaluating surface and upper-air data for the analysis are discussed, and charts are compared with macromaps. An experiment in determining patterns aloft at times other than when soundings are taken is also described.

CARLOS R. DUNN (Extended Forecast Section, U. S. Weather Bureau, Washington, D. C.) *Incorporation of Numerical Short-Range Prognoses in Five-Day Circulation Forecasts* One of the basic aids in the preparation of extended forecasts is a five-day mean midtropospheric chart centered on the day of the forecast, the unknown data being computed by autocorrelation techniques. Substitution of barotropic 24-hour and 48-hour numerical prognoses for the unknown periods automatically incorporates recent gains in short-period prognoses and permits computation of physical tendencies of the mean pattern. Comparison of the statistically and physically computed mean charts and their tendencies suggests superiority of the latter over North America and the Atlantic, but not in the Pacific where boundary errors in the barotropic prognoses presumably play an important role.

F. DONALD ECKELMANN (Lamont Geological Observatory, Columbia University, Palisades, N. Y.), J. S. BROWN (St. Joseph Lead Co., Bonne Terre, Mo.), AND J. LAURENCE KULP (Lamont Geological Observatory, Columbia University, Palisades, N. Y.) *Relationships between Lead Isotope Composition, Pattern of Mineralization, and Composition of Ore Solutions in the Bonne Terre Mine, Southeastern Missouri* The structural controls affecting movement of ore solutions in the Bonne Terre Mine include a prominent basement knob, sedimentary ridges, and organic reefs along ridge crests. The ridge-reef complex trends NNE-SSW with stratigraphically low ore to the northwest, low to high ore over the ridge-reef complex, and high ore to the east and southeast. Evidence favoring rising solutions includes (1) the step-like distribution of ore, (2) the restriction of high-level ore to areas over and adjacent to the tops of reefs, and (3) the location of ore, peripheral to the knob, immediately over the Lamotte sandstone pinchout surrounding the knob.

The Pb^{206}/Pb^{204} ratio varies regularly from 21.7 peripheral to the knob structure to 20.3 at outlying areas of mineralization. This regular variation along clearly defined channels suggests that galena was deposited uniformly from the knob outward or vice versa. Partial re-working or deposition of several generations of galena at one locality thus appear unlikely. This is also indicated by identical results for duplicate samples collected within one stope. The direction of variation in composition of mineralizing solutions with time depends on the relative age of marginally and centrally located ore.

J. I. EWING, J. F. HENNION (Lamont Geological Observatory, Columbia University, Palisades, N. Y.), AND C. B. OFFICER (Rice Institute, Houston, Texas) *Seismic Refraction Measurements in the Eastern Caribbean* In the summer of 1956, 30 seismic refraction stations were shot in the Venezuelan Basin, on the Aves Swell, among the islands of the Lesser Antilles and the Virgin Islands, and on a line northeast of the Barbuda across the extension of the Puerto Rico Trench. This paper presents the new data which add appreciably to the knowledge of crustal structure in the island arc and in the associated interior basin and deep-sea trench. The high-velocity crustal layer is found to be approximately parallel to topography throughout the region, appreciably thickened and with a somewhat lower velocity under the islands. Penetration to the mantle was achieved only in the deepest part of the Venezuelan Basin, in the bottom of the Puerto Rico Trench, and in the ocean outside the Trench.

R. M. FARQUHAR AND R. D. RUSSELL (University of Toronto, Toronto, Canada) *Anomalous Leads from the Upper Great Lakes Region of Ontario* We have previously reported on the presence of lead minerals of anomalous isotopic composition in the Sudbury, Ontario, mining area, and have used these anomalous isotope ratios in trying to determine the history and age of the Sudbury ores. We have since found a number of anoma-

lous leads in the upper Great Lakes region on Ontario, some of which are more anomalous than the most anomalous Sudbury galenas. As in the case of Sudbury, the anomalous leads vary enormously in isotopic composition, even when closely related geographically. Leads found in the Lake Nipigon region show extreme variation. There seems to be a correlation between isotopic composition and distance from the Lake Superior shore. Those leads nearer the shore have generally large radiogenic components. Leads some distance northwest of the lake are not apparently anomalous, having the isotopic constitution typical of the very old Keewatin leads. This paper attempts to explain some of the isotopic relationships noted for these leads and to compare and contrast them with the anomalous leads from Sudbury.

G. J. Ferber, L. R. Quenneville, and G. W. Reiss (Office of Meteorological Research, U. S. Weather Bureau, Washington, D. C.) *An Evaluation of a Simple Technique for Routine Fallout Determination* The U. S. Weather Bureau currently transmits twice-daily upper-air fallout (UF) winds. A standard has been developed to evaluate various techniques of fallout determination. Since the UF approach neglects the time and space variations of the wind, two simple modifications of this approach are proposed to partially overcome this deficiency. The UF method and its modifications are evaluated and comparative results are presented.

Sergio G. Ferraes (Institute of Geophysics, Ciudad Universitaria, Mexico, D. F., Mexico) *A Differential Equation for the Oscillation of a Magnet in the Geomagnetic Horizontal Field* Observations of magnetic horizontal intensity by the method of Gauss involve the determination of the period of oscillation of a suspended magnet. This development is aimed at establishing criteria that will be useful in designing the instrument in making such observations and in assessing their worth. The period is a function of the parameters of the ambient field, here considered to consist of a fixed component H and an oscillating component f, making a definite angle with H. A second-order differential equation describes the motion of the magnet and a condition is given for the period to be independent of the oscillating component of the field. More generally, two methods are outlined for solving the differential equation. The first leads to a Ricatti's equation. The second, using certain substitutions, yields an equation involving coefficients that can be evaluated by means of determinants.

Robert G. Fleagle (Department of Meteorology and Climatology, University of Washington, Seattle, Wash.) *A Linear Theory of Pressure Tendency and Vertical Velocity* Equations are derived from the linearized hydrodynamic equations which express the vertical component of velocity and the local rate of pressure change in terms of the south to north temperature gradient, static stability, latitude, and wave length. The wave length is eliminated, leading to equations which may be summed to describe actual superpositions of periodic disturbances of various wave lengths. Calculations of vertical velocity using the linear theory are compared with calculations using the adiabatic method, with calculations using relaxation methods and with cloudiness and precipitation. Linear theory gives results which compare favorably with results calculated from other methods, and it is relatively insensitive to errors in observation and analysis. Calculations of pressure tendency using the linear theory are compared with observations and with predictions made with the thermotropic model. The linear method is relatively sensitive to errors, but it has the advantage of expressing simply factors which are likely to result in rapid development.

Robert G. Fleagle (Department of Meteorology and Climatology, University of Washington, Seattle, Wash.) *The Temperature Distribution just above the Prairie Surface* The temperature distribution between heights of six and 50 cm was determined by measuring the vertical refraction of light beams over horizontal distances of from 20 to 500 yards. These observations reveal that at a height of about 12 cm above the relatively warm grass surface the air was warmer than would be expected from extrapolations from the distribution above or below 12 cm. This anomaly was persistent and was too large to be explained by random fluctuations. It may be explained as a consequence of radiative exchange between surface and air. The results suggest that it may be feasible in certain cases to calculate vertical heat flux directly from thermometric conductivity for air and observations of temperature gradient.

Robert F. Fudali (Department of Geophysics and Geochemistry, Division of Earth Sciences, Pennsylvania State University, University Park, Pa.) *On the Origin of Pseudoleucite* Three theories have been advanced for the origin of pseudoleucite: (1) Unmixing of leucite solid solution, (2) reaction between liquid and leucite, and (3) decomposition of potash analcite. Experimental studies at high temperatures and pressures have shown that water vapor lowers the solidus temperature of phonolite and raises the temperature of stability of the zeolite produced in the same compositions. The PT curves for the upper limit of zeolite stability and the beginning of melting of the phonolite approach each other as the water vapor pressure is raised. At a pressure of 4000 bars the two curves are only 30°C apart for the composition studied. It is expected that they will cross at higher pressures, the zeolite becoming stable at liquidus temperatures. It is therefore probable that pseudoleucite represents the decomposition product of zeolite phenocrysts. The effect of solid solution on the stability of zeolites is being studied in compositions along the join analcite-leucite. It appears probable that the PT curve for the breakdown of analcite will be raised as the composition approaches that of leucite. The composition of zeolite phenocrysts (pseudoleucite) and their enclosing matrix may give information on the depth at which magmas originate.

John C. Geyer and George T. Bryant (Johns Hopkins University, Baltimore, Md.) *The Travel Time of Radioactive Wastes in Natural Waters* Radio isotopes discharged into natural waters (1) precipitate and settle, (2) absorb on suspended and fixed surfaces,

(3) enter the biologic cycle, or (4) in solution move with the flowing, mixing water itself. In the course of its life a single nuclide may shift with more or less freedom back and forth among these alternates. The present paper deals with phenomena related to the fourth alternative. Natural waters and the substances carried in solution move and mix in response to complex forces of gravity, wind, tide, density, impact, shear, and inertion. Past studies of mixing and movement are drawn on to depict the time and space distribution of radioactive contaminates in natural waters. Tracer studies offer means for evaluating mixing and travel time which may in turn be used to forecast the fate of wastes continuously disposed of in water.

B. J. GILETTI AND F. BAZAN (Lamont Geological Observatory, Columbia University, Palisades, N. Y.) *Near-Surface Ocean Circulation from Tritium Measurements* The prethermonuclear level of tritium activity in the western North Atlantic was $T:H = 1.0 \times 10^{-18}$. Steady state analysis prior to 1954 shows that surface waters mix to the seasonal thermocline in less than five years. Post-1953 data show that mixing takes place in one year but local vertical inhomogeneities remain. A tritium activity equal to that of the North Atlantic surface water after the 1954 Castle tests was found off Brazil at 3° S latitude. North Atlantic Central water gives an 'age' of 25 years, which will be interpreted in the light of various theories of mixing.

Arctic Sea measurements indicate a flow rate for Chuckchi Intermediate Water (to be defined) of 14 km/yr from the Chuckchi Sea in a clockwise eddy to Ellesmere Island. The high tritium concentration ($T:H = 0.9 \times 10^{-18}$) at a depth of 400 m along the Ellesmere Island shelf is evidence for the formation and sinking to depth of water along this cost. A production rate of 1.1 tritium atoms/sec cm^2 Earth's surface by cosmic rays is calculated from the ocean data and suitable assumptions.

S. S. GOLDICH, A. O. C. NIER, AND H. BAADSGAARD (University of Minnesota, Minneapolis, Minn.) *A^{40}/K^{40} Dating of Rocks of the Lake Superior Region* A large number of rock samples from Minnesota and adjacent areas have been dated by A^{40}/K^{40} determinations on mica. The Northern Light gneiss, Minnesota-Ontario boundary area, is dated at 2.7 by. A number of samples between the Vermillion iron district and NW Angle, Minnesota, are 2.5–2.7 by. Gabbro (Duluth gabbro complex) intruding the Biwabik formation near Babbitt is 1.1 by, and a similar age was obtained for diabase from the Beaver Bay complex.

In east-central Minnesota the Thomson formation was involved in an orogeny accompanied by granitization and granite intrusion dating at about 1.7 by. The iron formation of the Cuyuna district and iron formations in northern Wisconsin and in Michigan were involved in this period of folding. Widespread graphitic beds indicate that plant life was developed prior to the 1.7 by orogeny, and correlation with the Biwabik and Gunflint formations, on geologic grounds, dates the algal and other fossil remains of these formations as older than 1.7 by.

Many of the granitic intrusions in central Minnesota formerly classified either as Algoman (pre-Animikie) or as Killarney (late Keeweenawan) are neither; they are properly assigned to the late Huronian-early Keeweenawan origeny (1.7 ± by).

ROSS GUNN AND B. B. PHILLIPS (U. S. Weather Bureau, Washington 25, D. C.) *An Experimental Investigation of the Effect of Air Pollution on the Initiation of Rain* Warm or unnucleated supercooled clouds will not usually precipitate unless moderate numbers of large cloud droplets (about 15 to 25 μ radius) are formed high above the cloud base. These droplets fall down through the cloud and grow into raindrops by accretion. New measurements in a giant expansion chamber show that the size of newly formed cloud droplets depends critically on the cleanliness of the processed air. Droplets formed in ordinary air are too small to grow, but droplets large enough to precipitate are immediately formed by condensation whenever the condensation nuclei density is sufficiently reduced. Since the activated nuclei density is usually observed to decrease rapidly with increasing altitude, the probability of generating droplets sufficiently large to initiate rain increases as the vertical development of a cloud system increases. The population densities of the large cloud droplets usually observed near the tops of precipitating clouds may be explained in terms of the cooling of an overlaying parcel of air that is initially relatively free of nuclei.

Since pollution is swept out of the atmosphere by diffusion onto cloud droplets and by droplet movement, it is suggested that periods of general cloudiness and precipitation act to reduce the original nuclei density. This permits the subsequently formed droplets to grow still larger, thus increasing the probability of appreciable precipitation. The rain-producing cycle is, therefore, provided with a feedback or regenerative mechanism which usually proceeds, in a given mass of air, until the air is appreciably desiccated. Condensation nuclei, as well as water vapor, usually accumulate simultaneously in fair weather. The presence of these nuclei may delay the initiation of precipitation until sufficient vertical instability can be established to lift or cool the relatively clean overlaying layers. The precipitation cycle may then be reestablished.

B. GUTENBERG (Seismological Laboratory, California Institute of Technology, Pasadena, Calif.) *Discrepancies between Thickness of the Crust Calculated from Seismic and from Gravity Data* About 30 years ago, it was widely believed that isostasy is mainly a consequence of local variations in density (horizontally or vertically) in the Earth's crust which compensate for differences in surface elevation. Today, prevailingly 'roots of mountains' are considered to be the main source for such compensation. Actually, both factors are involved. For example, under the Sierra Nevada in California effects of a 'root' seem to prevail, while immediately to the south under the Tehachapi Mountains or to the west under the Coast Ranges there is no indication of a root corresponding to the height of the mountains. Most apparent discrepancies between results from gravity data and from seismic data are a consequence of incorrectly assuming that isostasy results entirely from varying thickness of the crust with the same relatively low density everywhere. For pur-

poses of tectonic hypotheses calculations of gravity anomalies should be based on all relevant data available. A small quantity of anomalies calculated on the basis of complicated data is preferable to a large quantity based on simplified assumptions.

B. GUTENBERG (Seismological Laboratory, California Institute of Technology, Pasadena, Calif.) *Microseisms with Periods of About Two Seconds in Southern California* Despite termination in March 1956 of the project on microseisms sponsored by the Geophysics Research Division of the Air Force Cambridge Research Center, investigation of microseisms recorded by special instruments at Palomar and by routine instruments at other stations in Southern California was continued. This included microseisms having periods of about two seconds which are occasionally recorded in Southern California. Usually, their amplitudes increase with increasing turbulence of the air, especially after passage of a cold front. At Palomar they have a velocity of about 3½ km/sec and arrive from the direction of the coast.

Even when they record with relatively large amplitudes on vertical seismographs, the corresponding horizontal pendulum- and strain-seismograph records show only small motion. According to Ewing, Press, and Jardetzky, such motion of SV-type is to be expected in surface waves of second and higher modes. The two-second microseisms decrease much faster with distance than the usual six-second microseisms, and after traveling roughly 20 wave lengths they are no longer visible on any records.

MAURICE H. HALSTEAD AND R. L. RICHMAN (Department of Oceanography and Meteorology, Agricultural and Mechanical College of Texas, College Station, Texas) *The Micrometeorological Program of Texas A and M at O'Neill, Nebr., 1956* A series of profiles of wind, temperature, and humidity in the lowest 16 m, together with measurements of soil temperature and net radiation, were obtained with precision equipment at O'Neill, Nebr., during the summer of 1956 in support of USAF Project Prairie Grass. Both the instrumentation and observations are reviewed, and while special emphasis is given to the profile observations themselves, their use in turbulent transfer and heat-budget work is also discussed.

H. HAMAGUCHI, G. W. REED, AND ANTHONY TURKEVICH (Enrico Fermi Institute for Nuclear Studies, University of Chicago, Chicago, Ill., and Argonne National Laboratory, Lemont, Ill.) *The Uranium and Barium Contents of Meteorites* The uranium contents of three chondrites and an achondrite have been determined by a neutron-activation technique. About 10^{-8} gm U/gm of meteorite was found in the chondrites and ten times more in the achondrite. It was possible to determine that the isotopic composition is the same as that of terrestrial uranium to within ten per cent. The significance of the results with regard to Patterson's age measurements will be discussed. The barium content of all the objects was about 400 times greater than the uranium. The preliminary data on the uranium content of iron meteorites indicates even lower values than the 10^{-10} limits reported by Reed and Turkevich (*Nature*, v. 176, p. 794, 1955).

PAT J. HARNEY (Geophysics Research Directorate, Air Force Cambridge Research Center, Bedford, Mass.) *Aerograph Data from an L-20 Aircraft* As in 1953, airplane observations were used to get temperature and humidity in detailed soundings for Project Prairie Grass. A comparison of the meteorograph data with the radio-soundings shows characteristic differences. With the instruments used, neither furnished as much detail as desired. To make the airplane more useful the sensing-element lag was reduced and the altitude calibration rechecked. Useful new techniques were developed including low-level nighttime flights using a lantern-lit runway. Additional data were obtained using radiation balance measuring equipment developed at the University of Wisconsin.

MILES F. HARRIS (Office of Meteorological Research, U. S. Weather Bureau, Washington, D. C.) *An Investigation of 1000-500-mb Thickness Changes* The dynamic and advective terms in the thickness tendency equation of Sutcliffe and Forsdyke (1950) are evaluated on the assumptions of geostrophic divergence and geostrophic advection. Inclusion of the dynamic term in the tendency equation results in a slight but fairly consistent improvement in estimates of the 24-hour thickness change, over estimates based on advection alone.

The tendency equation is used to make 12-hour forecasts of the 1000-500-mb thicknesses at nine points over the eastern United States. These 'physical' forecasts of thickness are compared with statistical forecasts based on the serial correlation in the thickness values. The two methods are then combined by means of the multiple regression technique to obtain a third forecast. The three forecasts are compared with 12-hour numerical predictions of thickness at the same points.

RAE L. HARRIS AND ARIE POLDERVAART (Department of Geology, Columbia University, New York 27, N. Y.) *Zircons of Archean Rocks from the Beartooth Mountains, Montana and Wyoming* The uplifted Beartooth block of Montana-Wyoming consists of a core in which granitic gneiss predominates, surrounded by a mantle with predominant migmatites and metasediments. Detailed field studies carried out under a research project of a Columbia University team show that the granitic gneisses are autochthonous to parautochthonous members of the Granite Series. Zircon studies of samples from areas mapped in detail and including all major rock types except metabasaltic rocks, confirm this conclusion. Zircons are well-rounded and concentrates of all samples include crystals with outgrowths or complete overgrowths. Proportions of zircons with overgrowths generally increase the more granitic-looking the rock, but this also depends on the homogeneity of the terrane. Small lenses of granitic gneiss surrounded by migmatites and metasediments have fewer zircons with overgrowths than granitic gneisses taken from areas where this rock type predominates. Reduced major axes for lengths and widths of 200 zircons measured for each concentrate, vary from sample to sample. This emphasizes that the Beartooth granitic gneisses were formed from a heterogeneous sequence of sedi-

ments, and contrasts with the nearly identical zircon reduced major axes obtained for different samples of the same granitic pluton of magmatic origin.

H. S. HEAPS (Nova Scotia Technical College, Halifax, Nova Scotia, Canada) *Dependence of Internal Stress and Surface Strain upon Irregularities in an Elastic Solid* The present paper considers the effect of irregularities upon the stresses within an elastic material. The technique described may be applied to determine the effect of a variation of elastic constants upon any state of stress provided that the distance required for a significant variation in the original stress is large compared to the distance required for a significant variation in the elastic constants. A specific problem examined concerns the distribution of stress within, or around, a spherical region of increased elastic modulus. Also considered is the effect of such a spherical region upon the reading of a strain gage placed upon a neighboring plane boundary.

BRUCE C. HEEZEN (Lamont Geological Observatory, Columbia University, Palisades, N. Y.) *Deep-Sea Physiographic Provinces and Crustal Structure* On the basis of detailed echo-sounding profiles, the North and South Atlantic Oceans have been divided into a series of longitudinal physiographic provinces. Each province exhibits similar topographic detail and sediments throughout its length, and available geophysical data indicate that each is the surface expression of a major crustal structure. On the basis of less detailed data these provinces have been traced through the Indian Antarctic, South Pacific, Norwegian, and Arctic Oceans. A mid-ocean rift valley of remarkable continuity and seismicity divides each of the aforementioned ocenas into two equal parts. The province boundaries within each of the two major basins are strikingly parallel to the continental margins on each side and to the rift valley in mid-ocean. In explanation of this striking parallelism and symmetry an hypothesis of considerable increase in the volume of the Earth's mantle throughout geologic time is offered. Under this hypothesis the major structural features of the ocean are ascribed to tension and associated rift faulting.

W. A. HEISKANEN (Ohio State University, Columbus, Ohio) *The Columbus geoid* The author gives a summary of the preparatory work, collection of the needed gravity material, reduction method used, the gravity anomaly maps of different types needed, and the details of the method of computation of the geoid. Using the available material, 6479 squares of $1° \times 1°$, four times larger than was available in 1928, several new gravity formulas have been derived. The globe was divided into 36 longitude zones of 10°. A diagram and table give an idea of the corrections to the International gravity formula obtained from different zones. When all gravity observations made in the oceans are available, the equatorial value of the gravity might get a small negative correction.

The geoid in Europe, where already Tanni had rather good material, will remain nearly unchanged, but the geoid in America, in the Atlantic, and in India changes materially as a result of additional gravity observations, particularly at sea. Some samples of the geoid are given. The gravimetric deflections of the vertical at some astro-geodetic points of the arcs used by the Army Map Service last year for computing the dimensions of the Earth have been computed. Also, the astro-geodetically computed geoid of Europe, by Bomford is compared with the Columbus geoid.

ROLAND G. HENDERSON (U. S. Geological Survey, Washington 25, D. C.) *Downward Continuation of Anomalies in Magnetic and Gravity Fields* Theoretically, magnetic and gravity anomaly fields observed over a plane on the Earth's surface can be continued analytically below the plane to the level of the nearest singular point. An adequate practical method is as follows: The integral solving the Dirichlet problem for the plane is used to compute the anomaly at a number of evenly spaced points above a given point on the plane (upward continuation). Continuation below the plane is then effected by means of a Lagrange extrapolation polynomial passed through these points. Formulas are derived that permit the calculation of downward extensions conveniently by either desk calculator or electronic digital computer. In a similar manner, formulas for the first and second vertical derivatives of the fields are derived. The processes are applied to theoretical and practical anomalies.

S. W. HENRIKSEN, S. H. GENATT, M. Q. MARCHANT, AND C. D. BATCHLOR (Army Map Service, Washington 25, D. C.) *Surveying by Occultations* A method of surveying which uses data obtained from photoelectrically observed occultations is described. The method is applicable in those cases where it is desired to connect triangulation systems which are too widely separated to be tied together by the usual means. The discussion includes the prediction and reduction of occultations. From the reduction of one occultation observed by teams in different geodetic systems, a line of position is obtained. A second similarly observed occultation yields a second line of position and hence a fix.

J. P. HEPPNER, J. D. STOLARIK, AND L. H. MEREDITH (Naval Research Laboratory, Washington 25, D. C.) *Rocket Measurements at WSPG, New Mexico, July 5, 1956: Part A, Altitude Distribution of Nightglow Emissions; Part B, The Magnetic Field to 163 km* (A) Four photometers measured the night-sky emissions OI 5577 A, OI 6300 A, NaI 5893 A, and background light intensities near 5335 A. The photometers were oriented to view 5° off the rocket's vertical axis such that a decreasing signal would be observed in passing vertically through a light-emitting region. The emitting region of the oxygen green line λ5577 was entirely between 90 and 120 km and had a very sharp lower boundary. The region of emission of the oxygen red lines λλ6300–6364 was not entered, indicating that this emission occurs at altitudes >163 km. The sodium *D*-lines, λλ5890–5896, were encountered between approximately 85 and 105 km. Exact limits on this region are indefinite due to the low intensity of the emission compared to the cumulative background emissions. Comparison of background variations in these photometers with that in the λ5335 photometer indicate that OH emissions occur primarily below 90 km and are at least as low as 56 km where the photometers

were first 'uncapped' to view the night sky. On re-entering the 114- to 88-km region a bright light was observed in the wake of the rocket. The spectral distribution resembles that of the first Positive System of N_2. This phenomenon suggests that active nitrogen may be present in the region of the green line emission.

(B) Absolute total scalar magnetic field measurements were taken twice per second to an altitude of 163 km using a proton precessional magnetometer. Observatory records indicate that this was a typical, magnetically quiet night. Analysis to date has not revealed an ionospheric discontinuity of more than ten gammas which is approximately the 'noise' level imposed by rotation of the magnetic field of the rocket instrumentation.

J. B. Hersey, E. T. Bunce, R. F. Wyrick, and F. T. Dietz *Seismic Study of the Ocean Floor Southeast of the Blake Plateau* Thirty-nine seismic refraction reversed and end-to-end profiles are reported in three distinct topographic provinces east of Carolinas and Georgia: (1) the continental shelf, (2) the Blake Plateau, and (3) the deep ocean to the east, which here consists of an interior basin about 2600 fathoms deep separated from the Nares Deep and North America Basin by a low ridge which trends southeastward from the continental slope opposite Cape Fear and recurves to the southwest toward the Bahamas. On the shelf seismic results are a straight-forward extension of known structures beneath contiguous coastal areas. In the deep ocean, crustal structures are more complicated than the typical ocean sequence, always giving evidence of a sequence of several layers having velocities intermediate between soft sediments (cir 1.8 km/sec) and M-layer velocities (7.8–8.5 km/sec). The ridge is underlain by the most complicated series of layers, while the interior basin is the simplest. North of the ridge there is evidence of a considerable thickness of crustal rocks, the M-layer occurring at depths as great as 21 km. The Blake Plateau consists principally of a north-south trending syncline bordered to north and east by complex faulting. Some evidence exists for supposing crustal rocks (to the M-layer) to be about 15 km thick beneath the Blake Plateau. Velocity versus depth-of-overburden relations in this area support the findings of Nafe and Drake.

H. H. Hess (Princeton University, Princeton, N. J.) and W. R. Thurston (National Research Council, Washington, D. C.) *Disposal of Radioactive Waste on Land* Two years consideration of the disposal problem by the National Research Council committee has led to certain conclusions which are presented. Waste may be safely disposed of at many sites in the United States but conversely there are many large areas in which it is unlikely that disposal sites can be found as for example the Atlantic seaboard. The research to ascertain feasibility of disposal has for the most part not yet been done. The most practical immediate solution of the problem suggests disposal in cavities mined in salt beds or domes. Disposal could be greatly simplified if the waste could be gotten into solid form of relatively insoluble character. Disposal in porous beds underground has capabilities of taking large volumes but will require considerable research to make the waste compatible with such an environment. The main difficulty with this method at present is to prevent clogging of pore space as waste is pumped in.

Walter H. Hoecker, Jr. (Office of Meteorological Research, U. S. Weather Bureau, Washington, D. C.) *Life History and Measurements of Scottsbluff Tornadoes of June 1955* Fairly complete tornado life histories have been synthesized from over 100 still photographs and eight strips of color movie film taken of two tornadoes near Scottsbluff, Nebr., in June 1955. From the still photographs funnel height and width measurements have been made and from the movies translational and rotational speeds have been determined at a few points. Evidence of downward air motion in the immediate vicinity of both tornadoes was found and in one instance cloud elements acting as airparcel tracers demonstrated the downward motion. Sample measurements of both vortices are shown and the method used in making the measurements is illustrated.

Walter E. Hoehne (Naval Research Laboratory, Washington, D. C.) *The Use of a Constant-Volume Balloon for High-Altitude Soundings* The introduction of ¼ mil mylar plastic film makes possible the production of a light-weight high-altitude sounding balloon which may be of meteorological interest. A manufacturer's preproduction model of such a balloon, weighing 7½ pounds, has been flight-tested by the Navy and its merits as a sounding balloon to the 100,000-ft level are considered.

B. J. Hollingsworth and H. I. Meyer (Research Dept., United Gas Corp., Shreveport, La.) *Two-Dimensional Gravity Drainage Profiles* An electronic computer was used to determine the shape of the free surface in a two-dimensional gravity drainage system. Classical methods of hodograph transformation and conformal mapping were used. A table of contour coordinates for different geometrics presents the results of these computations. Some problems which arose in this type of numerical analysis are mentioned. The method of successive steady states was used in an attempt to apply these results to a type of transient drainage problem. The results of this analysis are compared with those of analog experiments using a Hele-Shaw type of simulator.

Leith Holloway (Office of Meteorological Research, U. S. Weather Bureau, Washington, D. C.) *Correcting for Unavoidable Smoothing of Artificial Satellite Data* Terrestrial data, such as long-wave radiation, obtained by non-directional sensors on artificial satellites will be unavoidably space-smoothed because the satellite will 'see' a large segment of the Earth at one time. The nature of this smoothing is discussed and methods are presented for partially reversing this smoothing and thereby restoring some of the spatial variation filtered out of the data.

D. W. Holmes and L. F. Hafer (Observations and Station Facilities Division, U. S. Weather Bureau, Washington, D. C.) *Recent Developments in the Weather Bureau's Upper-Air and Radar Programs* Expansion of the upper-air programs of the Weather Bureau, both

in terms of the number of stations and the kind and complexity of soundings is outlined, as well as procurement plans for new equipment designed to obtain winds aloft to high altitudes under all weather conditions. The current state of the radar program including installation plans for the future is discussed. A brief resume of the characteristics of the present and planned equipment is presented.

DONALD W. HOOD, KILHO PARK, AND J. B. SMITH (Department of Oceanography and Meteorology, A and M College of Texas, College Station, Texas) *Bicarbonate Ion as a Source of Carbon for Marine Plants, and Its Oceanographic Significance* By means of C^{14} tracer techniques it has been shown that certain pure cultures of marine plants utilize bicarbonate ion as their primary source of carbon for photosynthesis. Respiration of both plants and animals appears to yield molecular carbon dioxide. Hydration of the carbon dioxide is required to complete the cycle in water with low hydroxyl ion concentration. The effect of the above is to create a greater partial pressure of carbon dioxide in the euphotic zone of the sea than is in equilibrium with the over-all carbon dioxide system. Some preliminary data will be presented to indicate the rate of hydration of carbon dioxide in sea water and the extent of excess partial pressure of carbon dioxide which may occur in the sea.

ROBERT A. HOOVER (U. S. Weather Bureau Airport Station, Washington, D. C.) *Empirical Relations between the Maximum Wind and Central Pressure of Hurricanes Entering the Coast North of Jacksonville and the Maximum Height of the Surge* Surge profiles are used to determine the maximum height of the surge for hurricanes entering the Atlantic Coast north of Jacksonville, Florida. The relation of these heights to the maximum winds and central pressures of the hurricanes is shown.

WILLIAM E. HUBERT (U. S. Navy, Joint Numerical Weather Prediction Unit, Washington, D. C.) *Numerical Sea-Condition Forecasts* Since July 1956 the Joint Numerical Weather Prediction Unit at Suitland, Maryland, has been making 36-hour machine forecasts of sea conditions on an operational basis. These prognoses are based on the 1000-mb wind forecasts derived from the two-level, thermotropic model currently in use at JNWP. Two different sea-forecast models have been tested to date. The first model utilized only the forecast winds at the end of the forecast period and therefore yielded 'fully developed waves.' A more complete model incorporating 'duration' is now in use. This paper describes both methods and compares the numerical results with observed conditions.

DARRELL S. HUGHES (Dept. of Physics, University of Texas, Austin, Texas) AND ROBERT G. MCQUEEN (University of California, Los Alamos Scientific Laboratory, Los Alamos, N. Mex.) *Density of Basic Rocks at Very High Pressures* The density of two gabbros and one dunnite have been measured at several pressures in the range from 150 to 750 kb (one kilobar = 986.2 atmospheres). These pressures were attained in shock fronts generated by high explosives. The densities were computed from the observed shock waves. The dunnite, initial density of 3.25 gr/cc, was compressed to a density of about 4.93 gr/cc at 720 kb. The gabbros, initial density 3.00 gr/cc, were compressed to 5.00 gr/cc at 750 kb. Both gabbros show evidence of a polymorphic transition at some pressure between 100 kb and 350 kb to a more dense, but less compressible phase. Agreement obtained from these data with a crust of dunnite 400 km thick underlain by a gabbroic rock with Bullen's Model A is very close.

P. M. HURLEY, W. H. PINSON, H. W. FAIRBAIRN, AND R. F. CORMIER (Massachusetts Institute of Technology, Cambridge, Mass.) *Comparison of A^{40}/K^{40} and Sr^{87}/Rb^{87} Ages on Biotite* By use of induction fusion without flux, titanium metal for gas purification and mass spectrometer connected to system, argon measurements can be made in two hours with a precision close to one per cent. The constants $\lambda_\beta = 4.72 \times 10^{-10}$/yr; $\lambda_\epsilon = 0.557 \times 10^{-10}$ yr; $BR = 0.118$ for K^{40}; and $\lambda_\beta = 1.39 \times 10^{-11}$/yr for Rb^{87}, give the tentative comparison of results shown below.

Granite	A-K age	Sr-Rb age	Ratio
	my		
Conway, New Hampshire	175	170±7 pct	1.04
Larry's River, Nova Scotia	320	330	0.97
Albany Cross, Nova Scotia	385	365	1.05
Lake Gaspereau, Nova Scotia	390	370	1.05
Bear River, Nova Scotia	390	370	1.05
Ship Harbour, Nova Scotia	390	400	0.98
Creighton granite, Sudbury, Ont.	1360	1245	1.09
Rockville granite, Minnesota	1690	1620	1.04
St. Cloud granite, Minnesota	1860	1775	1.05
Sacred Heart granite, Minnesota	2530	2330	1.08
Average ratio			1.04

Argon ages in the Minnesota rocks were determined by S. S. Goldich, but we agree with his argon analysis within experimental error.

J. ALLEN HYNEK AND FRED L. WHIPPLE (Smithsonian Astrophysical Observatory, Cambridge, Mass.) *Instrumentation for the Observation of the IGY Satellites* The program for optical tracking of the IGY satellites consists of three distinct parts: the visual search and tracking program, of low-order accuracy, the photographic tracking program, of high precision, and a computation center. The precision program will use special Schmidt cameras of aperture 20 inches, mirrors of aperture 30 inches and focal lengths of 20 inches. The use of strip film (55 mm) and a third axis of rotation makes possible short exposure times during bright twilight conditions. The telescopes should photograph 15-inch spheres to a distance of 1000 mi and three-foot spheres to the Moon's distance. The visual observations will be carried out by amateur

groups throughout the world, operating in groups. They will use binoculars and monoculars, covering fairly wide areas of the sky, each group providing a meridian passage. The optical and computational program will find, follow, and predict the motion of each satellite and, by exact measures of the orbit, provide scientific data not obtainable otherwise.

W. S. JARDETZKY (Mahattan College, New York, N. Y., and Lamont Geological Observatory, Columbia University, Palisades, N. Y.) *On the Possibility of an Aperiodic Pole Shift* The existence of 'drowned' islands in western and central Pacific areas investigated by Hess, the distribution of free-air gravity anomalies corresponding to the longitude terms noted by Jeffreys, and the displacements of the equatorial reef belt shown by Schwarzbach are phenomena from different fields which among many others could be associated with an aperiodic pole shift. It seems that a base for a plausible explanation of each of these three independent phenomena is obtained if the deformations of the Earth's body due to the pole shift are accounted for. Some data concerning these phenomena indicate also the probability of horizontal displacements on a large scale in several parts of the Earth's crust.

C. Y. JOHNSON, J. C. HOLMES, AND E. B. MEADOWS (Naval Research Laboratory, Washington, D. C.) *Ion Composition of the Ionosphere at Fort Churchill, Canada, by Rocket-Borne Spectrometers* Aerobee-Hi rocket, NRL-48, was instrumented with the prototype IGY three-tube Bennett radio-frequency mass spectrometer experiment to study the neutral gas and positive and negative ion composition of the upper atmosphere. The rocket was launched from Fort Churchill, Canada, at 23h 21m CST, November 20, 1956, and attained a peak altitude of approximately 250 km. Spectra were obtained from the positive ion spectrometer in the mass range 53 to 6 AMU for 375 sec while the rocket was above 90 km. Mass 30 was the first positive ion detected and it remained in the spectra throughout the flight. Positive ions of mass 32 and 16 subsequently appeared in the spectra. The mass 16 positive ion became the predominant ion with increasing altitude. Two minor positive ions of mass 28 and 18 were detected during the flight. A possible identification of these ions is $32 - O_2^+$, $30 - NO^+$, $28 - N_2^+$, $18 - H_2O^+$, $16 - O^+$. Above 170 km there is indirect evidence of a positive ion with relatively large abundance at mass 63 ± 2 AMU. A spectral peak in the region of mass 46 was detected by the negative ion spectrometer. Nitric acid, one of the rocket's propellants, might have contributed to some of these ion peaks, although data from the neutral gas spectrometer at the nose of the rocket indicated that the rocket was 'clean.'

J. V. JORDAN, G. C. LEWIS, AND M. A. FOSBERG (University of Idaho; Moscow, Idaho) *Tracing Moisture Movement in 'Slick-Spot' Soils with Radiosulfur* Preliminary greenhouse tests using 'slick-spot' soil and associated soil in columns indicated that Co^{60} and S^{35} moved through the soil columns and appeared in the first drainage water. The first field experiments were run south of Boise on the Seebree-Chilcott associated series. Radiosulfur was used in the form of dilute sulfuric acid soaked in absorbent cotton. Each wad was specifically placed in or adjacent to a 'slick-spot.' After several months, soil samples from these tagged 'slick-spots' indicated that some characteristic water movement had occurred. Improved techniques have been developed and the study will expand to include 'slick-spot' soils in irrigated and dryland areas.

S.-K. KAO (University of California, Los Angeles, Calif.) *On the Oscillation of Air Particles and Its Effects on Trajectory in the Atmosphere* This paper presents a study of free and forced oscillations of air particles in the atmosphere. Solutions of the Lagrangian hydrodynamic equations are obtained for air particles subject to different types of forcing functions. The problem of stability and types of trajectories of air particles are discussed.

WILLIAM H. KLEIN (Extended Forecast Section, U. S. Weather Bureau, Washington, D. C.) *An Objective Method for Predicting Five-Day Mean Temperatures* Linear multiple regression equations are derived for predicting five-day mean anomalies of surface temperature at a network of stations in the United States from data centered four days earlier. The basic forecasting parameters are five-day mean anomalies of 700-mb height and temperature, surface temperature, sea-level pressure, and 700–1000-mb thickness at standard grid points in the Western Hemisphere. From values of these data during the past ten Januarys, a few predictors are selected in stepwise fashion by repeated calculation of fields of simple and partial correlation coefficients on the IBM 701 computer. The results will be interpreted synoptically, tested on independent data, and compared to the official (subjective) forecasts. The method may be readily applied to the forecast routine, and predictions can be made in a few minutes by use of a desk calculator.

LEON KNOPOFF (Institute of Geophysics, University of California, Los Angeles, Calif.) *The Generation of Love Waves* The classical problem of Love waves in a low-velocity layer overlying a half-space has been solved for the case of a line source located in the upper layer and vibrating with a pure SH motion. This two-dimensional problem conveniently has a solution in terms of contributions from the infinite set of images of the source taken in the two boundaries. If the ray from an image to the point of observation makes an angle with the vertical less than the critical angle for the layered structure, then the signal from the given image arrives as a 'body wave' and is very rapidly attenuated with distance in the Earth's surface. If the ray angle is greater than the critical angle, then the motion has two important parts: an early refraction, becoming more prominent for the later refractions, and a dispersive, strong, direct S-arrival; this direct S-wave has the properties of a guided wave rather than a body wave. The train of guided waves lengthens as the epicentral distance increases. A graphical solution of the more important features is presented, illustrating the development of Love waves, calculated from a 'first-motion' approximation.

OLAVI KOUVO (Department of Geology, Princeton University, Princeton, N. J.) AND PAUL W. GAST (Lamont Geological Observatory, Columbia University, Palisades, N. Y.) *Comparative Radioactive Ages from Some Finnish Granites* Radioactive ages based on the decay systems, $Rb^{87} \rightarrow Sr^{87}$, $K^{40} \rightarrow A^{40}$, and U, Th $\rightarrow$ Pb have been determined for two post-kinematic granites. These studies suggest a similar age of 1650 m y for the granite of Bodom and the large Rapakivi intrusive of southwestern Finland. Some Rb-Sr ages appear to be significantly low. Isotopic composition of Sr for the whole rock and Sr from accessory calcium minerals such as apatite and fluorite has been studied to determine to what extent radiogenic Sr may exchange between different mineral phases. A less detailed study on a late kinematic karelidic oligoclase granite gives an age of 1800 m y.

M. P. LANGLEBEN (McGill University, Montreal, Quebec, Canada) *Multiple-Level Radar Maps of Precipitation Patterns* A new system of scanning and display make possible sets of constant-altitude radar maps of precipitation, one every few thousand feet. In winter, these reveal a well-defined pattern of generating cells aloft on occasions when there is no pattern at lower levels. Winter cold fronts are preceded by successions of bands; warm fronts involve an alternation between patterned and diffuse snow formation. These diffuse formations aloft have been observed to evolve into well-marked patterns. Low-level snow showers resemble generating cells in being small and numerous. Summer showers are larger, more intense, and more widely scattered. The new technique permits the study of the life cycle of individual showers in detail, displaying as it does the whole pattern every 3.6 min. On days of low relative humidity aloft, the shower echoes are relatively small and firm. On other days, snow plumes up to 100 mi long develop, and persist after the firm cores have disappeared. For research, such as relating the storm pattern to surface hail reports, the new pictures are synthesized photographically. An operational system has been devised in which the synthesis is electronic and immediate. A system of multiple displays at standard levels of 850, 700, 500, and 300 mb is envisaged.

LEONARD H. LARSEN (University of Cincinnati, Cincinnati 21, Ohio) AND ARIE POLDERVAART (Columbia University, New York 27, N. Y.) *Zircons of the Bald Rock Batholith, California* Bald Rock batholith was studied by R. R. Compton, who supplied samples for this investigation. The pluton consists of a trondhjemite core grading into a mantle of granodiorite and tonalite. Zircon studies show that two populations of zircons are distributed throughout the batholith, one composed of simple prismatic crystals and the other of complex stubby individuals. Most rocks have mixtures of both zircon types. Proportions of the two types vary systematically, from predominant simple prismatic zircons in the core of the pluton to predominant complex stubby crystals at its margins. These observations contrast with other studies of individual granite plutons of magmatic origin which have established that such igneous bodies contain single zircon populations. The distribution of two distinct zircon populations in the Bald Rock batholith, as well as structural relations demonstrated by Compton, are explained in terms of a paraautochthonous intrusive of migma-magma, with solid phases predominant at the borders of the pluton and silicate melt predominant in the core. The two zircon types then represent complex stubby crystals formed in the solid phases and long prismatic individuals crystallized from magma. Other possibilities—mixing of two magmas, magmatic immiscibility, or assimilation—seem unlikely.

RAY K. LINSLEY (Stanford University, Stanford, Calif.) *Correlation of Rainfall Intensity and Topography in Northern California* As part of a long-range program on the hydrology of small watersheds, a correlation between the two-year, one-hour rainfall intensity at 126 recording rainfall stations in northern California and related topographic and climatic parameters has been made. The resulting correlation has a coefficient of correlation of 0.88 and a standard error of 0.067 in/hr. With this relation, it is possible to show the variation of rainfall intensity over the area in much greater detail than has hitherto been possible from observed intensity data alone. This paper discusses the parameters employed, the methods of correlation, and the results obtained.

R. J. LIST (U. S. Weather Bureau, Washington, D. C.) *The Concentration of Nuclear Debris in the Air as a Meteorological Variable* During the summer of 1956, the U. S. Public Health Service operated a network of 30 stations which measured the concentration of long-lived radioactivity in the air near the ground. Several cases of meteorological interest are discussed, indicating the possible usefulness of this type of measurement for meteorological research.

GERALD R. MACCARTHY (University of North Carolina, Chapel Hill, N. C.) *The Virginia Earthquake of August 27, 1833* This earthquake, scarcely mentioned in seismological literature, appears to have been moderately severe in central Virginia, where its intensity is estimated to have been 5 to 5½ on the modified Mercalli scale. The disturbed region formed a broad ellipse with an area of approximately 52,000 mi^2 which trended NE-SW. The region of greatest disturbance appears to have been between Richmond and Charlottesville. It was preceded by 'earthquake noises' in the Alexandria, Virginia, area and, if we may believe the contemporary reports, by weak foreshocks near Lynchburg, Virginia. North to south it was felt from Baltimore to Raleigh, and east to west from Norfolk to Lexington. Rumbling noises were everywhere reported except in the peripheral area. No appreciable damage seems to have been caused, although Thomas Jefferson's grand-daughter, living near Charlottesville, wrote that she "feared the chimney might be shaken off," and two Negro coal miners were killed during a panic in a coal mine a few miles west of Richmond. Stephen Taber, in one of the few printed references to this quake, mentions that fences were visibly shaken in Louisa County.

NICHOLAS E. MANOS (Air Pollution Medical Program, Public Health Service, Washington, D. C.)

Meteorology in Air Pollution The Air Pollution Medical Program of the Public Health Service has been given the responsibility for supporting, encouraging, and conducting research on the possible health effects of smog and other forms of air pollution. Meteorology enters the picture both in trying to discover what harm to health is being done by air pollution and in trying to discover what components of air pollution are causing these harmful effects. Weather elements such as wind speed and atmospheric stability are obvious factors in determining the intensity of pollution over various cities. In addition, weather elements such as temperature and humidity have an effect on the progress of certain diseases and on the length of life for persons disabled from given disabilities. It is to this latter effect of weather that I want to draw the particular attention of meteorologists. As we begin to get clues from the various researches on the health effects of air pollution, we will become increasingly interested in learning more about the effects of various weather elements on comfort, sickness, and death rates in various areas of the country. We will want to separate the harmful effects of weather, which are largely beyond our control, from the harmful effects of air pollution, so that the latter can be identified and brought under control. We have already received considerable help from the Office of Climatology, U. S. Weather Bureau.

NICHOLAS E. MANOS (Air Pollution Medical Program, Public Health Service, Washington, D. C.) *Tornadoes Spread Disease* The hypothesis was presented at these meetings two years ago that tornadoes are spreading histoplasmosis, a recently discovered lung disease which resembles tuberculosis. It was predicted that the frequency of infections might increase in northwestern Mississippi after the tornado-like storm of February 1, 1955. That prediction proved to be correct. Data showing the increase are presented.

ELWOOD MAPLE (Geophysics Research Directorate, Air Force Cambridge Research Center, Bedford, Mass.) *Sub-Audio-Frequency Geomagnetic Fluctuations at College, Alaska* Measurements of the integrated level of the fluctuations in a 20 to 45 cycle/sec band have been under way since December 1956 with the cooperation of the Geophysical Institute, University of Alaska, and are being continued. At most times the fluctuations originate in distant lightning strokes as reported by Holzer and Deal. The average diurnal variation is that to be expected from the worldwide variation of thunderstorm activity and the directional characteristics of the detector coil.

Unusually high fluctuation levels (greater than about 140 pct of the average level to be significant) precede by several hours the main magnetic disturbances (as measured by the local K index) with which they are associated. Of the two large disturbances ($K = 7$) which occurred during the first 47 days of data, only one was preceded by a significantly high fluctuation level (160 pct maximum of average level). Two lesser disturbances (sustained levels of $K = 6$) occurred, and both were preceded by significant increases (210 pct maximum in each case). Smaller disturbances (including single occurrences of $K = 6$) were not associated with significantly high sub-audio fluctuation levels. The magnetic disturbance effect appears weaker than that previously observed at Point Barrow, which suggests a strong dependence on geomagnetic latitude.

WILBUR MARKS (David Taylor Model Basin, Washington 7, D. C.) *The Directional Spectrum of a Wind-Generated Sea, Part I, Method of Observation and Data Reduction*—Stereo photographs from two aircraft flying in tandem and wave pole records obtained by the RV *Atlantis* were obtained. Special instrumentation designed at Woods Hole Oceanographic Institution was required for the stereo photographs. The planning of the operation required close coordination between WHOI and the U. S. Navy Hydrographic Office. Weather data were simultaneously obtained by the RV *Atlantis*. The stereo data were read as spot heights on a grid of points 30 ft apart, 90 points high, and 60 points wide.

ROYAL R. MARSHALL (Enrico Fermi Institute for Nuclear Studies, University of Chicago, Chicago, Ill.) *Common Leads and the Continuous Development of the Crust* The isotopic compositions of most lead ores vary systematically with their geologic ages. These non-anomalous leads show that, to a first approximation, they originate in reservoirs which have been chemically closed in respect to lead, uranium, and thorium throughout geologic history. Recently Houtermans and his coworkers introduced a 'model' lead-lead age based on primeval lead. From their isotopic analyses of a large number of ores, they calculated the U^{238}/Pb^{204} and the Th^{232}/U^{238} ratios which would be present today in the reservoirs. The latter ratio was observed to increase with age.

The secular trend of the thorium to uranium ratio has been confirmed by the more than 200 mass spectrometric analyses which have been published. Furthermore, a similar but less obvious change with age of the U^{238}/Pb^{204} ratio occurs. Such secular variations (about five per cent change in 3 b yr (billion years) in the uranium to lead ratio and somewhat greater than ten per cent for that of thorium to uranium) could be spurious, but examination of the basis of the calculation and the errors in the values involved indicates a geologically significant process. Some process appears to be adding lead relative to uranium to the crust of the Earth from a source with a higher lead to uranium ratio. Similarly, uranium is being added relative to thorium. However, the rate of enrichment of uranium may be nearly three times that for lead. Isotopic ratios of lead ores can be corrected for the addition of primeval lead and brought into agreement with their evolution through the decay of uranium and thorium in effective chemically-closed systems

JOHN E. MASTERSON (Geophysics Branch, Office of Naval Research, Washington, D. C.) *The Use of Rocket-Ejected Chaff and Metalized Parachutes to Measure Winds above 100,000 Feet* Small rockets are used to carry chaff or metalized parachutes to above 100,000 ft where they are ejected as radar targets to measure wind speeds and directions. Parachute measured winds are correlated with existing balloon soundings with favorable results. Wind speeds are within eight knots and directions are within ten degrees. The computation

of the wind speeds and directions at altitude is rapid and direct.

JOHN F. MCCLAY AND PAUL F. FOUGERE (Air Force Cambridge Research Center, Bedford, Mass.) *Preparation of Mutually Consistent Magnetic Charts* Conditions of mutual consistency for the magnetic elements are determined from the facts that (1) the Earth's total magnetic intensity vector field is irrotational, and (2) the orthogonal components of the total intensity vector everywhere satisfy the Pythagorean theorem. These conditions are applied to quadratic polynomials for the magnetic elements. There result analytic expressions for the elements which not only fit the data adequately but also satisfy the consistency conditions.

R. E. MCCROSKY AND GERHARD F. SCHILLING (Harvard College and Smithsonian Astrophysical Observatories, Cambridge, Mass.) *Luminous Intensities from IGY Satellites during the Last Flight Stages* The physical theory of meteors describes semi-quantitatively the kinematic and mass loss phenomena of a meteroid entering the Earth's atmosphere at velocities between ten and 70 km/sec. The same theory is applied to the problem of an artificial Earth satellite entering the atmosphere. The luminosity produced by the satellites has been computed as a function of the heat transfer coefficient between the atmospheric gases and high-speed solid objects. A single visual observation of 'satellite-meteor' during the last flight stages might be sufficient to determine, to better than an order-of-magnitude, the effective heat transfer for bodies entering the upper atmosphere at the lower range of meteor velocities. The determination of this constant will be an aid in the application of the photographic meteor method to derive upper atmospheric densities through clarification of the processes of meteor fragmentation. The plans of the visual observation program of IGY Earth satellites include provisions for attempting to obtain the necessary luminosity data which then will be readily applicable for a verification of the method developed.

H. W. MENARD AND R. L. FISHER (Scripps Institution of Oceanography, La Jolla, Calif.) *Clipperton Fracture Zone in the Northeastern Equatorial Pacific* Clipperton fracture zone has been extensively sounded for 2000 miles west of Central America and is divisible as follows: (127°–113°W long) A broad low welt 900 mi long has a central trough about 20 mi wide and at most 4200 ft deep. North of the welt the sea floor is 150–200 fathoms deeper than to the south. Four northwest-trending troughs averaging 30 mi in length and with 6000 ft maximum relief are evenly spaced about 200 mi south of the zone. (113°–107°W) Clipperton Island is one peak on a volcano-studded ridge 60 mi wide and 330 mi long, with a deep narrow trough on the north side. Maximum submarine relief is 13,200 ft and maximum average slope is 17°. A northeast-trending trough 100 mi long and with relief of 10,000 ft lies 150 mi north. (102°–101°W) A low welt with a central trough 2000–3000 ft deep transects the Albatross Plateau. (101°–96°W) The expected east-west trend of the fracture zone has no obvious topographic expression; instead, a branching feature, the Tehuantepec Ridge, trends 400 mi northeast to the continental margin. It has the topography of a typical submarine fracture zone with relief of 8000 ft.

JAMES H. MEYER AND J. R. BAUER (Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, Mass.) *Microvariations of Water Vapor in the Lower Troposphere* Variations of water vapor in the troposphere are calculated from simultaneous airborne measurements of radio refractive index and temperature obtained with a microwave refractometer and an aerograph employing a sensitive bed thermistor. The partial pressure of water vapor is calculated from the well-known formula

$$e(mb) \cong 2.7\,(n-1)\,T^2 - 2.1 \times 10^{-4} pT$$

where n is the refractive index, T is temperature in degrees Kelvin, and p is total atmospheric pressure in millibars. In cases where airborne measurements of temperature were not available, radiosonde temperature data were employed to estimate the fluctuations of water vapor from the refractometer data. One important result of these studies is the identification of extremely thin stratifications in the troposphere across which the water vapor fluctuates on the order of millibars over thicknesses of the order of meters.

ARTHUR R. MILLER (Woods Hole Oceanographic Institution, Woods Hole, Mass.) *Report on the Effect of Winds on Coastal Water Levels of New England* Tidal records from Nantucket Sound, Cape Cod; Montauk, Long Island; and Portland, Maine, have been studied along with wind and barometric observations from each location. Results of this study show that departures from mean sea level due to wind are made manifest by dual combinations of symmetrical and asymmetrical responses to wind which are characteristic of the individual localities. The symmetrical term refers to sinusoidal variation of sea-level departures as a function of wind direction and applies to the outer coast and general level. Asymmetry of sea-level response to wind depends on the very local topography and fetch lengths about the observing station. The interplay of these two features allows for a scalar variety of sea-level departures subject to wind direction, duration, and field size, as well as barometric adjustment. Time-lag between peak winds and maximum sea-level departures is probably dependent on the dominance of either the symmetrical or asymmetrical characteristics as well as the size of the effective wind field.

R. G. MILLER, G. M. HOWE, AND D. G. FRIEDMAN (Travelers Weather Research Center, Hartford, Conn.) *An Evaluation of Certain Synoptic-Climatological Aids to Weather Forecasting* Enough experience has now been accumulated with the use of the synoptic-climatological method in daily forecasting to permit a preliminary appraisal of its usefulness. It is concluded that stochastic methods can be applied to give numerical predictions of the sea-level and 500-mb patterns that are of use to the forecaster.

WALTER MUNK AND FRANK SNODGRASS (Scripps Institution of Oceanography, La Jolla, Calif.) *Some Recent Results in the Study of Ocean Waves in the Band*

of 1 to 100 Cycles per Kilosecond Power spectra of Vibroton wave records have revealed two quite distinct phenomena: (1) For frequencies between 50 and 80 c/ks the spectrum is dominated by dispersive signals, starting at about 50 c/ks with an rms amplitude of one mm, and then increasing in frequency by about ten per cent per day. We have analyzed three such sequences, separated by about three to four days. Very likely these signals come from Southern Hemisphere storms, and the earliest arrivals may have been generated in the Indian Ocean. (2) The spectrum for frequencies less than 50 c/ks is characterized by a remarkably complex fine structure. The details are reproducible from day to day, and do not reveal any dispersive shifts in frequency. This part of the spectrum is believed to be due to the normal modes associated with the local bottom topography.

WALTER H. MUNK (Scripps Institution of Oceanography, La Jolla, Calif.) *Rotation of the Earth: A Geophysical Discussion* Irregularities in the observed motion of stars have long been interpreted in terms of irregularities in the rotation of the Earth. These have been a nuisance to the astronomers and an asset to the geophysicists. Semi-annual and shorter period fluctuations in the length of day are associated with bodily tides. An annual term is largely caused by winds. Irregular changes from one decade to the next appear to be caused by electromagnetic coupling of the mantle to a turbulent core. A secular change since Egyptian time is due largely to tidal friction, but sea-level and atmospheric tides play a significant part.

An annual wobble in the position of the pole is caused by shifts in air mass. The damping of the 14-month wobble is presumably caused by imperfections in the elasticity of the mantle. In addition, there has been some paleomagnetic evidence for a long-term wobble, polar wandering. Some of these problems go back to Victorian times, but there have been a number of new developments during the last few years. A marked improvement in observational methods now promises further headaches to the astronomer, and fun for the geophysicist.

JOHN E. NAFE AND CHARLES L. DRAKE (Lamont Geological Observatory, Columbia University, Palisades, N. Y.) *A Comparison of Deep and Shallow Water Marine Sediments* The variation of compressional wave velocity with depth of overburden in marine sediments of the eastern continental shelf of North America is shown to be distinctly different from that in adjacent ocean basins. The approximate linear representations of the velocity-depth data differ in slope by a factor of four.

By means of an empirical relation connecting compressional velocity and porosity, based on data from bore holes and deep-sea sediment cores, estimates are made of the depth variation of porosity, density, shear-wave velocity, rigidity, and incompressibility for both the shallow and deep-water sediments. At a given depth of overburden (water excluded) porosity is less in shallow-water sediments than in deep-water sediments. Results are compared with experimental and observational data from artificial compaction studies, well logs, and some new seismic refraction profiles on which both compressional and shear waves along paths within the sediments are found.

HOMER E. NEWELL, JR. (Naval Research Laboratory, Washington 25, D. C.) *The Scientific Uses of Artificial Earth Satellites* If all goes as planned, a number of small artificial satellites of the Earth will be launched during the International Geophysical Year. The IGY satellites will be launched by means of a finless three-staged rocket weighing about 11 tons. The satellites will be small, weighing on the order of 21.5 pounds. To make the utmost use of this small weight, the instrumentation must be miniaturized as much as possible, using such things as transitors and ferrite cores, and the most efficient power-supply systems obtainable. Nevertheless, there is a considerable list of worthwhile experiments that might be done in such a small satellite, including observations of solar radiation, cosmic rays, the Earth's magnetic field, the ratio of radiation influx to the atmosphere to the radiation efflux, micrometeors and dust in space, the cloud cover over the Earth, auroral particles, the density of the upper atmosphere, and geodetic parameters. The first four experiments have already been selected by the Technical Panel for the Earth Satellite Program to be attempted during the IGY. Since the last two listed require only careful observation of the satellite's motion, they will certainly be done also. The initial IGY satellites will open a new frontier of science, of engineering, and of Man's achievement. The future possibilities of research from such space vehicles is exciting to contemplate, particularly in the light of possible increases in total payload weight, and increased flexibility in the choice of orbital inclinations and altitudes.

T. OBAYASHI AND J. A. JACOBS (Geophysical Laboratory, University of Toronto, Toronto, Canada) *Sudden Commencements of Magnetic Storms and Atmospheric Dynamo-Action* In order to explain the worldwide current systems for the sudden commencement of magnetic storms, a dynamo action in the upper atmosphere with enhanced conductivity is considered. Assuming the main source of electromotive force generation is in the polar region, tentative wind systems, responsible for the D_s field of sudden commencement, are estimated. The change at sudden commencement is so abrupt (within a few minutes) that it is reasonable to assume that the wind system in the ionosphere will not change. Thus, the change from the S_q field to the D_s field at a sudden commencement may be considered as due only to the enhancement of the conductivity of the ionosphere in the polar region. Therefore, the problem is reduced to that of finding a consistent wind system which could produce the observed current systems both for the quiet day and the sudden commencement, assuming a reasonable change in conductivity. A consistent wind system is found by combining a diurnal and a semidiurnal term. Possible physical mechanisms of the sudden commencement of magnetic storms are also discussed.

JOHN A. O'KEEFE (Army Map Service, Washington 25, D. C.) *Geodesy and the Artificial Satellite* This paper states the principal geodetic quantities which

are to be extracted from the observation of the artificial satellite, and gives the errors with which these quantities may be expected to be obtained from radio tracking on certain assumptions.

H. A. Panofsky and A. K. Blackadar (Department of Meteorology, Pennsylvania State University, University Park, Pa.) *On the Theory of the Formation of Turbulence by Horizontal Windshear* An equation is derived for the conditions of maintenance of large eddies by isentropic windshear on the basis of the eddy energy budget. Some speculations are presented as to the effect of these eddies on the production and maintenance of patchy small-scale turbulence.

Frank L. Parker (Oak Ridge National Lab., Oak Ridge, Tenn.) *Tracers in Hydrologic Studies* The use of radioactive tracers to study phenomena in hydrology that have not previously been amenable to investigation is proceeding at a rapid pace. A group of experiments was carried out in lakes and reservoirs in Massachusetts to determine eddy diffusion coefficients. The average eddy diffusion coefficient divided by the radius of the eddy was found to be 0.013 ft/sec. A group of experiments to determine the average velocity of streams and the dilution in streams by use of radioactive tracers was then performed. The diffusion coefficients found in the test of the streams were compared with the theoretical diffusion coefficients of G. I. Taylor for straight pipes and found to be larger due to the increased dispersion caused by bends and obstructions in the stream. A mathematical formulation for general use in determining dilution and dispersion in rivers and streams by radioactive tracers was established. A correction is made for the absorption and decay of the isotope depending upon its chemical and nuclear properties. Work is under way to delineate further the absorption coefficients of important isotopes under various conditions leading to a better determination of the eddy diffusion coefficient.

Sverre Petterssen (University of Chicago, Chicago, Ill.) *Physical and Statistical Approaches to the Problem of Weather Prediction* Although the formulation of the problem of weather forecasting as an initial-value problem goes back to 1904, it is only within the last decade that substantial progress has been made to obtain useful predictions by integrations of the equations of motion. While primitive statistics have always been useful as an adjunct to empiricism in practical forecasting, it is only within the last pentade that substantial progress has been made to develop rigorous statistical forecasting procedures. The general structure of the two approaches, present limitations, and hopes for the near future are discussed, and some verification data will be represented to show present capabilities.

Willard J. Pierson, Jr. (Department of Meteorology and Oceanography, New York University, New York 53, N. Y.) *The Directional Spectrum of a Wind-Generated Sea, Part II, Analysis of Data and Results* The wave-pole data were used to compute a highly reliable frequency spectrum which was corrected theoretically for the motion of the wave pole. After consideration of non-linear effects and the effects of the variation of the meteorological elements, the frequency spectrum showed remarkable agreement with the results of Neumann. The stereo data were used to compute a directional spectrum. After considerable difficulty due to a number of different factors, a reliable directional spectrum was obtained. Agreement between the integral over direction of the directional spectrum and the frequency spectrum was obtained. The angular spread of the important wave frequencies was determined.

W. D. Potter (Bureau of Public Roads, Washington 25, D. C.) *Relations between Low and High Frequency Peak Rates of Runoff* Maximum annual peak rates of runoff plotted on extremal probability paper in accordance with Gumbel's distribution of extreme values were divided into two groups; one representing the low- and the other the high-frequency events. Average probability curves were determined for each group for 70 watersheds having periods of record of from 26 to 48 years. Relations were established between the ten-year peak determined from the high-frequency curve and the ten-year and 50-year peaks from the low-frequency curve. The standard error of estimate for these relations was ± 10 and ± 20 pct respectively. Tests were made to find the minimum length of record required to determine with sufficient accuracy the ten-year high-frequency peak. The criterion used was whether or not the average relations between this peak and the long-record ten-year and 50-year low-frequency peaks remained the same as those originally established, and whether the standard errors remained the same. This minimum length of record was found to be ten years. As a result of these tests, it was concluded that the relations established between the two frequency groups of peaks may be used in conjunction with short periods of record to improve the precision of estimates of low-frequency peaks.

Frank Press (Seismological Laboratory, California Institute of Technology, Pasadena, Calif.) *Crustal Structure from Phase Velocity of Rayleigh Waves* A critical evaluation of the phase-velocity method for investigating crustal structure is given. The method has been applied to Southern California, the Sierra Nevada, and the San Francisco Bay region. In the latter region the crustal thickness was found to be 30 km, in agreement with Tocher's results from explosion seismology, providing a valuable check. Crustal thickness in the coastal regions of California is less than reported for inland regions, an effect of proximity to the continental margin. The Coast and Peninsular ranges seem to have little effect on crustal thickness. The decrease in phase velocity across the Sierra Nevada may be interpreted as indicative of crustal thickness about 50 pct greater than normal.

Frank Press (Seismological Laboratory, California Institute of Technology, Pasadena, Calif.) *Internal Friction in the Mantle and Rigidity of the Earth's Core* Amplitude ratios of multiple reflected ScS waves can be used to determine the reflection coefficient at the mantle-core interface, providing the absorption coefficient for mantle shear waves is known. Although the absorption coefficient for mantle Rayleigh waves is

known, there is some doubt as to whether it may be applied to shear waves. Results from ultrasonic model experiments show systematic differences in absorption coefficient for compressional, shear, and Rayleigh waves. At present ScS measurements can provide only maximum values for internal friction in the mantle and core rigidity.

D. W. PRITCHARD (Chesapeake Bay Institute, Johns Hopkins University, Baltimore, Md.) *On the Question of Non-Tidal Drift in Estuaries* Continuity considerations show that in an estuary with sectional homogeneity in salt content the upstream flux of salt necessary to maintain the salt balance cannot be produced by mean advective processes, but must rather be related to horizontal eddy diffusion. For such estuaries, several investigators have stated that non-tidal drift (NTD) can be expressed as

$$NTD = R/AF$$

where R is the volume rate of inflow of fresh water into the estuary, A is the cross-sectional area of the estuary at the point in question, and F is the fraction of fresh water present. The compatibility of this expression with basic continuity concepts is examined. An explanation of the apparent anomaly between observed drifts and continuity requirements is given.

GEORGE R. RAPP, JR. (Department of Geophysics and Geochemistry, Division of Earth Sciences, Pennsylvania State University, University Park, Pa.) *The Synthesis of Zoisite in the Pressure Range 1000-5000 Bars* Zoisite has been synthesized by hydrothermal techniques in the pressure range 1000 to 5000 bars. It has been found to crystallize well from two different starting materials, (1) gel of zoisite components, and (2) an unknown hydrous phase crystallized at low pressures and temperatures. Well-formed crystals suitable for single crystal x-ray studies have been produced in gold foil envelopes in cold seal bombs. The reaction is very sluggish and it has not been possible to obtain 100 pct yields, although the amount of zoisite increases with the length of run at least up to 30 days. The upper temperature limit for the syntheses indicates that zoisite breaks down, univariantly, by the reaction

$$6\,\text{Zoisite} \rightleftharpoons 6\,\text{Anorthite} + 2\,\text{Grossularite} + \text{Corundum} + 3\,H_2O$$

There is some uncertainty as to the exact composition of the grossularite—it may well be hydrogrossularite. A natural low-iron zoisite has been decomposed above the *PT* curve for the reaction. Zoisite has not been synthesized from glass or from anorthite. The *PT* curve for the above reaction will undoubtedly give way at low pressures and temperatures to a *PT* curve for a reaction involving other hydrous phases, whereas at higher pressures the curve will be replaced by one involving an assemblage of high-density phases.

F. A. RECORD (Massachusetts Institute of Technology, Round Hill Field Station, South Dartmouth, Mass.) *Diffusion Measurement Techniques Used during Project Prairie Grass* Sulfur dioxide gas, released for ten-minute periods from a continuous point source near ground level, was used as a tracer in the diffusion experiments. Average gas concentrations were determined at selected points downwind from the source from changes in the electrical conductivity of absorbing solutions. At each sampling station, a known volume of air was bubbled through ten milliliters of slightly acidified hydrogen peroxide solution; sulfur dioxide present in the air sample was converted to sulfuric acid, thereby increasing the conductance of the solution. Diffusion patterns representative of both thermal stability and instability are briefly illustrated.

K. G. REINHART (Northeastern Forest Experiment Station, U. S. Forest Service, Parsons, W. Va.) *Calibration of Five Small Forested Watersheds* On the Fernow Experimental Forest in West Virginia, five forested watersheds, 38 to 96 acres in area, have been gaged by the U. S. Forest Service since 1951. The watersheds are close together, for the most part contiguous, and are quite similar in topography, soil, forest cover, and stream-flow characteristics. This is the first time a group of watersheds has been calibrated for forest watershed research involving determination of the effects of a range of cutting treatments; the methods and problems of calibration should be of interest to other investigators in this field. After calibration, four watersheds will be cut over, using four different cutting practices. One watershed will be used as a control. Effects of treatment on stream flow will then be measured. Methods of Wilm and of Kovner and Evans were used to determine length of calibration period based on an analysis of annual, monthly, peak, and low flows. Problems of treatment assignment are discussed.

HERBERT RIEHL AND DAVE FULTZ (Department of Meteorology, University of Chicago, Chicago, Ill.) *The General Circulation in a Dishpan Experiment with Steady Long Waves and Jet Stream* At first the general circulation in the experiment is described. Then the heat and momentum balance is presented in cylindrical coordinates, followed by computation of heat and energy budgets in a coordinate system attached to the jet stream axis. The two points of view of looking at the general circulation are compared.

WYNDHAM J. ROBERTS (State Water Survey, Urbana, Ill) *Suppressing Evaporation from Water Surfaces* The Illinois State Water Survey Division in 1954 developed an evaporimeter for year-around recording of losses from water surfaces. Two evaporimeters were filled with plain water, but the water surface of Gage 2 was treated with hexadecanol. The graphs indicated substantial reductions in loss from the treated pan. Even greater differences occurred between two three-foot deep identical buried water containers. In August 1956 hexadecanol was used in a 100,000-gallon capacity concrete basin of 14-ft maximum depth. Tests through October using alternately coated and plain water surfaces showed considerable reduction of loss. Under laboratory conditions, hexadecanol may reduce natural water loss from that basin by one-half during the warmest summer days and at least by 20 pct during the cooler spring and fall months.

During 1957 it is planned to carry this experiment to a large recreation lake in Illinois. Many Illinois

water supply reservoirs store nearly 50 pct of their capacity in their top three feet. Normal evaporation exceeds three feet in the southern half of the state where reservoirs provide most municipal supplies. Reducing evaporation by 30 pct would be equivalent to a 15 pct increase in Illinois reservoir storage capacity.

ELIZABETH RONA (Oak Ridge Institute of Nuclear Studies, Oak Ridge, Tenn.) *A Method to Determine the Isotopic Ratio of Thorium^{232} to Thorium^{230} in Minerals* An ever-increasing interest prevails in the geological distribution of thorium and in the thorium content of uranium minerals. If the thorium content is low, the conventional methods are not sensitive enough to determine less than 0.01 pct, especially if very small amounts of thorium have to be analyzed in the presence of large amounts of uranium. The method described in this paper does not attempt the determination of absolute amounts of thorium, but rather the isotope ratio Th^{232} to Th^{230}. The thorium was separated from the mineral. The amount of Th^{232} was determined by activation analysis and that of Th^{230} by counting its alpha particles. The ratio of the two isotopes was calculated by comparing the beta and alpha activity of the two thorium isotopes in the sample to those of the standard of known Th^{232} to Th^{230} ratio. This ratio was determined for 11 uranium minerals.

CLARENCE S. ROSS (U. S. Geological Survey, Washington 25, D. C.) *Welded Tuffs from a Deep Well in Southeastern Georgia; Volcanism of Probable Early Paleozoic in the Georgia-Florida Region* A suite of drill cores from a depth of about 4000 ft from Clinch County, southeastern Georgia, merit description because they disclose a type of volcanism not previously recognized in the region and also because they contribute to the much broader story of igneous activity in the Georgia-Florida region. The record of volcanism begins with a fine-grained volcanic conglomerate, composed of andesite and welded tuff fragments of dacitic character. These are partly rounded and have been transported to their present position. Above that is about 35 ft of rhyolitic welded tuff which represent deposition directly from an ash flow. Above the ash-flow tuffs is a recurrence of the transported volcanic conglomerate materials.

The volcanic materials have undergone low-grade metamorphism represented by replacement with laumontite, but without detraction from the relationships. The studies of Paul L. Applin of the U. S. Geological Survey indicate that these materials belong to the Lower Paleozoic rocks of the region and that the direct ash flow represents volcanic activity at that time. On the other hand, the andesite and dacite fragments are older, but how much older is problematical. They may also be derived from Lower Paleozoic rocks, or they may be from Precambrian ones.

J. E. R. Ross (Geodetic Survey of Canada, Ottawa, Canada) *Reciprocal Crossings in Geodetic Leveling* The Geodetic Survey of Canada, in extending lines of precise levels, has been required to connect bench marks separated by bodies of water as much as a mile wide. With considerable experience in the field and by subsequent analysis of results, a method of crossing has been perfected which provides the leveler a means by which no loss in accuracy occurs in the water portion of the line.

Reciprocal observations on the rods are considered a must. The movable-target method has been adopted because of speed and economy. The method chosen provides a maximum number of simultaneous reciprocal observations without a sacrifice of accuracy for speed. Modern communication equipment has done much to improve the efficiency of the operation, and the methods outlined lend themselves nicely to its use. The intention of this paper is not to produce a new method of crossing to the exclusion of those in use by other surveys, but rather to interpret some qualities of other methods.

MALCOLM D. ROSS (Office of Naval Research, Washington, D. C.) *Use of Time-Lapse Cameras at High Altitude for Observing Weather Dynamics* A constant-level plastic-balloon system employing time-lapse motion photography for hurricane research is described. The system was developed under the Office of Naval Research Project Hurricoon. Miscellaneous cloud photographs taken from high altitude balloons are presented to illustrate the potential of this new meteorological tool. Results of a Hurricoon feasibility study are discussed and general plans for its use in the summer of 1957 are presented. Application of this concept with time-lapse motion photography (or in some cases television) is suggested for studies of more frequently observed dynamic situations such as cumulus clouds, thunderstorms, and frontal activity.

MALCOLM D. ROSS (Office of Naval Research, Washington, D. C.) and M. LEE LEWIS (Bureau of Aeronautics, Washington, D. C.) *High-Altitude Manned Balloons for Further Meteorological Research* A manned constant-level plastic-balloon program of the Office of Naval Research, entitled Project Strato-Lab, is discussed. Systems have been developed and tested to permit scientific observations in the atmosphere from zero velocity platforms at many different interesting altitudes. The various systems permit research ranging from low levels in the troposphere with 'open basket' gondolas to high stratospheric altitudes with a pressurized gondola. Some information is presented regarding flight profiles and observations made during recent ascents. Possibilities are outlined for future Strato-Lab meteorological research.

ROBERT E. RUSKIN (U. S. Naval Research Laboratory, Washington, D. C.) *An Aerograph for Humidity-Temperature Soundings from Aircraft* An aerograph indicator-recorder with interchangeable vortex thermometer-hygrometer probe for airplane use and trailing-bomb type sensor housing for helicopter use provides a digital indication and a digital with superimposed graphical record of humidity, temperature, and pressure, along with a digital record of time. A cylindrical carbon-type hygrometer element surrounds the resistance thermometer element at the center of the vortex in the axial-flow vortex thermometer. For normal flight speeds no correction to the temperature and pressure data is needed. Humidity in terms of

dew point or vapor pressure is read from a curve using the humidity and temperature digital readings.

FREDERICK SANDERS (Department of Meteorology, Massachusetts Institute of Technology, Cambridge, Mass.) *Some Relationships between Vertical Velocity and Weather* The large-scale mid-tropospheric vertical velocity is estimated by combining a dynamical contribution derived from Sutcliffe's theory and an orographic contribution. The resulting values, which are highly correlated with the vertical motions computed from numerical-prediction models, may be easily computed from conventional map analyses. Comparison of these vertical velocities with simultaneous weather phenomena indicate considerable success in the specification of precipitation and of clear sky or scattered cloud conditions in the United States, but regional differences are apparent. Limitations of the method are discussed.

J. DOYNE SARTOR (Rand Corporation, Santa Monica, Calif.) *The Force and Electrical Field between Cloud Droplets in a Uniform Electrical Field* Expressions are derived for the force of attraction and the local electrical field between uncharged and charged cloud droplets as they approach each other in a uniform electrical field. Computed values of the force and field for a number of droplet separations are presented, illustrating the strong magnification of the field between the near surfaces of the droplets and the rapid increase in the force of attraction as they approach one another. Implications of the results to droplet growth, droplet charging, and ion production are discussed.

IRVING I. SCHELL (Department of Geology, Tufts University, Medford, Mass.) *On the Nature of Tropical Storm Relationships* A 25-year series of sea surface temperatures, winds, and cloudiness over several areas in the tropical Atlantic between latitudes 20° N and 4° S was examined with regard to the frequency of tropical Atlantic storms during two eight-year periods and one nine-year period. During the first two periods the average tropical storm frequency was 6.1 and 5.8 per year, respectively, and these values were associated with below-average sea temperatures and above-average wind speeds during the August–October season in the intertropical convergence zone and during the preceding months in the northeast trade-wind belt. During the nine-year period the average storm frequency was 12.1 per year, and was associated with above-average temperatures and below-average wind speeds in both areas during the August–October season and preceding months, respectively. It is also concluded that the lack of tropical storms in the South Atlantic is due to the fact that the zone of favorable wind and temperature conditions during the Southern Hemisphere summer remains near the equator where the Coriolis force is too weak for storm development.

IRVING I. SCHELL (Tufts University, Medford, Mass.) *On the Role of the Oceans in the Climates of the Pleistocene* Simpson's concept for an increased circulation, greater cloudiness, higher precipitation, lower temperatures, and a resulting glaciation due to an initial increase in solar radiation is contradicted by the greater poleward transport of heat with increased circulation and by the observed greater glaciation with less precipitation though with more snow as shown by recent evidence from Iceland.

The role of the oceans through a greater storage of heat during periods of higher temperature and sinking of chilled surface water to the bottom during periods of lower temperature and its effective withdrawal from interaction with the atmosphere for long afterwards, was to make the interglacial stages longer than the glacial ones. The increase in the thickness of the ice from the pole to latitudes 65° to 50° N over Europe and North America resulted from the increasing width of the North Atlantic ocean and greater availability of moisture for the storms to draw on. The temperature differences between the glacial and interglacial stages derived from analyses of the snowline and ocean cores when considered together with the observed changes in recent decades point to small fluctuations in solar radiation as capable of producing the greatly contrasting climates of the Pleistocene.

ALLEN H. SCHOOLEY (U. S. Naval Research Laboratory, Washington 25, D. C.) *Short-Fetch Water Wave Slope Probability Distributions* Probability distributions of slopes of wind-disturbed water surfaces for various wind velocities were reported by Cox and Munk and by Schooley in 1954. The results are in good agreement in the direction of the wind for wind speeds between five and 25 knots even though different methods of measurements were used and the locale of the measurements was the Pacific Ocean in one case and the Anacostia River in the other. Since the fetches in the two cases were widely different, this agreement infers that if the fetch does affect the distributions the effect is of secondary importance, or it is present for fetches of less than about 1000 ft.

This paper gives the results of measurements of slope probability distributions for a fetch of about 15 inches using a small water-wind tunnel. For this extremely short fetch the mean square slope was found to be higher than the previous longer fetch data for wind velocities greater than about ten knots. At 18 knots the short-fetch mean square slope was 15 pct higher. Cox and Munk reported a peakedness of slope distributions that was barely above the limits of observational error. Further evidence of peakedness was found in the short-fetch data. The mean value of the distributions was measured to reach a maximum in the downwind direction and was about 1.5° in the region of 18 knots.

LLOYD R. SETTER AND CONRAD P. STRAUB (Robert A. Taft Sanitary Engineering Center, U. S. Public Health Service, Cincinnati, Ohio) *The Distribution of Radioactivity from Rain* Fallout radioactivity, largely as precipitation, has been monitored continuously at Cincinnati, Ohio, since the spring of 1953. Supplemental studies on rain, cistern, and surface water samples were made to determine the distribution and characteristics of the activity. Two years of continental testing revealed that the predominant air contaminant was young fission products and the deposition of activity from rain was variable and occasionally quite high. On June 1, 1957, the estimated residual activity from

fallout during 1953, 1954, 1955, and 1956 will be 10, 12, 50, and 105 $m\mu c/M^3$, respectively, of fission products (nine months to four years of age).

Based on young fission product fallout (15 to 60-day old) it is estimated that $\frac{1}{4}$ of the fallout is solubilized by rain. Of the remaining $\frac{3}{4}$, about 20 pct is held by solid surfaces such as vegetation, and about 80 pct is associated with air particulates. Depending on the cover crop and the intensity of rainfall, it may be assumed that most of the activity is fixed near its point of deposition. Tests of surface waters support the supposition that little of the fallout can be accounted for as runoff.

R. J. SHAFER (Eastern Air Lines, Atlanta, Ga.) AND W. L. SOMERVELL (U. S. Navy Project AROWA, Naval Air Station, Norfolk, Va.) *Objective Forecasting for the Norfolk (Va.) Area* Aids to forecasting precipitation, dense fog, temperature changes, and sea breeze at Norfolk (Va.) Naval Air Station are presented.

W. W. SHINNERS AND J. A. SHIRLEY (Observations and Station Facilities Division, U. S. Weather Bureau, Washington, D. C.) *Recent Developments in Marine Instruments and Observations* Improvements of a major nature in marine instrumentation for merchant ships are described as well as several experimental programs to test new equipment. The current status of the program to take radiosonde observations aboard merchant-type vessels is presented.

ANATOL J. SHNEIDEROV (Polycultural University of America, Washington 6, D. C.) *The Hearth Hypothesis of the Constitution of the Earth* Recent theories on the continental wandering, and the previously published theories on the continental drift indicate and imply that Africa was at one time one continent with South America, Antarctica was a joint land with the Indian subcontinent, and at some earlier time all dry land was a single surface massif of the Earth. Such a separation of the original massif into continents is required by the author's hypothesis of the expanding Earth. A scrutiny of the contraposed coasts, and their geological structure is in a fair agreement with the hypothesis. The exponential theory of gravitation (*Trans.*, v. **44**, pp. 61–88, 1943) requires a considerably higher temperature at the center of the Earth than it is now generally accepted, and, as a consequence, a quasi-liquid Earth core and a hearth at the center of it. In *Priroda*, no. 7, July, 1956, B. A. Magnitskii presents a diagram of the constitution of the Earth according to V. N. Lodochnikov (USSR) and W. H. Ramsey (England). The facts that their theories also require for the core a temperature considerably higher than 3000°C, and some similarity of Magnitskii's diagram with that published by the author in 1943 (noted above) made him review his hypothesis of the expanding Earth. The result is presented in the hearth hypothesis which, in the opinion of the author, may explain the origin of the Earth's magnetic field and the seismicity.

SAM SHULITS AND GORDON D. BENNETT (Pennsylvania State University, University Park, Pa.) *Eddy Viscosities in Open Channels* The quest for open-channel turbulence parameters, particularly for the prediction of velocity profiles, reveals that the number most frequently used, the von Karman 'universal' k, varies at least from 0.2 to 0.4. No systematic grouping seems to have been found for these experimentally derived values of the von Karman 'constant.' If, instead, the eddy viscosity (or exchange coefficient) is examined, not only is an orderly trend observable, but this trend can be explained plausibly.

E. S. SIMPSON (Ground Water Branch, U. S. Geological Survey, Mineola, N. Y.), W. A. BEETEM (Quality of Water Branch, U. S. Geological Survey, Denver, Colo.), AND F. H. RUGGLES (Surface Water Branch, U. S. Geological Survey, Atlanta, Ga.) *Radiotracer Experiments in Mohawk River, New York, to Study Sewage Path and Dilution* Sewage from the Knolls Atomic Power Laboratory near Schenectady, N. Y., was dosed with P^{32} prior to discharge into the Mohawk River. Its pattern of diffusion was measured in the river by immersible GM-tubes and by sampling. The initial path of the sewage was strongly influenced by differences in density between sewage and river due to temperature. During warm months relatively cold sewage moved on the river bottom toward the deepest part of the channel perpendicularly to the river current. For about the first 1000 ft of travel the maximum sewage concentration decreased logarithmically with distance from outfall. The term 'half distance' (here about 100 ft) is proposed to describe the concentration change. During cold months sewage rose to the river surface and at times was moved upstream by wind. However, when the river temperature was near freezing, the sewage first rose and then sank as the temperature of the sewage-river mixture approached 39°F. The background activity of river water and mud was sensitive to fallout from nuclear weapons tests, affecting test results. The background was treated as a function of a random variable because sample-to-sample differences in activity were greater than the statistical error of individual measurements.

S. F. SINGER (Physics Department, University of Maryland, College Park, Md.) *Further Developments in the Magnetohydrodynamic Theory of Magnetic Storms* A previous theory of magnetic storms is expanded in order to take account of the following topics: (1) the spatial distribution of the ring current around the Earth; (2) the stability of the ring current; (3) the connection between the ring current and the aurora; and (4) the question of the acceleration of the auroral particles and the instability of auroral forms. Finally, some experimental methods are discussed, including detecting the existence of protons in the aurora by means of the nuclear reactions which are produced by their capture by atmospheric nitrogen. Gamma rays emitted in this reaction should penetrate deep into the atmosphere and be detectable at airplane altitudes.

JOSEPH SMAGORINSKY (Office of Meteorological Research, U. S. Weather Bureau, Washington, D. C.) *The General Circulation Research Program of the U. S. Weather Bureau* A program for the investigation of the dynamics of the general circulation utilizing high-speed computational means is described. The objectives are, roughly, (1) the construction of models of increas-

ing complexity that are capable of explaining the observed features of the general circulation and which are applicable to the study of climate and long-range prediction, and (2) the concurrent study of the details of some of the associated physical processes such as convection and turbulent transfer and condensation, in order to incorporate them eventually into more refined general circulation models.

J. V. SMITH (Department of Mineralogy, Pennsylvania State University, University Park, Pa.) AND TH. G. SAHAMA (Institute of Geology, Helsinki, Finland) *Phase and Structural Relations in the Nepheline-Kalsilite System* Phase relations in the system nepheline-kalsilite have been studied by experimental methods (Tuttle and Smith) and by examination of the mineral assemblages in alkaline rocks (Sahama). Fourteen phases have been characterized, namely, high- and low-nepheline; high- and low-carnegieite; o- and d-kalsilite; orthorhombic $KAlSiO_4$; tri-kalsiliet; tetrakalsilite; natural, anomalous natural, and synthetic kaliophilite; O2; and a complex form of nepheline.

The feature of the phase diagram that is of most importance to petrology is the miscibility gap between kalsilite and nepheline ($Na_3KAl_8Si_8O_{16}$). Kalsilite, the stable form of $KAlSiO_4$ at low temperatures, inverts to orthorhombic $KAlSiO_4$ near 850°C. It is likely that several of the phases are metastable under the conditions in which they were synthesized. All the phases, except carnegieite, are structurally related to high-tridymite. The two forms of kalsilite probably differ only in the distribution of Si and Al atoms. The complex form of nepheline may be similarly related to ordinary nepheline.

WARREN SMITH (Office of Meteorological Research, U. S. Weather Bureau, Washington D. C.) *Mesoanalysis of a Tornado-Producing Situation in Texas* Some significant findings are presented showing the relation of the macroscale synoptic patterns expanded to the mesoscale and illustrated by a series of maps showing a detailed analysis of surface conditions in Texas just prior to and during the destructive tornado outbreak of May 25–26, 1955. These hourly maps indicate the development and movement of mesosystems and the interrelation of the parameters of pressure, temperature, precipitation, and radar from a time when the pressure field is relatively undisturbed until the pressure disturbance moves out of the network area. Evidence of the formation of a disturbance area was found prior to any such indication from regularly reporting stations or radar reports.

FRANK SNODGRASS AND WALTER H. MUNK (Scripps Institution of Oceanography, La Jolla, Calif.) *Off-Shore Recording of Ocean Waves in the Band of 1 to 100 Cycles per Kilosecond* Off-shore recordings of ocean waves have been made in conjunction with a shore-based tsunami recorder. A Vibrotron transducer converts bottom pressure into frequency, which is recorded aboard. Accuracy is better than one part in 100,000. About two dozen stations have been occupied on the continental shelf and borderland off Southern California, and in the vicinity of Guadalupe Island off the coast of Mexico. Range in depths has been from ten to 700 m. Usable tide records have been obtained.

EDGAR W. SPENCER (Department of Geology, Columbia University, New York 27, N. Y.) *Fracture Patterns in the Beartooth Mountains, Montana and Wyoming* Fracture patterns in the Precambrian core of the Beartooth Uplift have been studied. In an area of 700 sq mi, 25,000 fractures measured at 250 stations, show a regional pattern reflected in major structural trends of the Middle Rocky Mountains. Many larger fractures which extend for miles are filled with Precambrian dolerite and metadolerite dikes, and indicate strong Precambrian structural control of Laramide deformation in this region. The strike and length of 2100 joints on the southwestern slope of the uplift have been measured on aerial photographs and are compared with ground measurements. Significant directions of steep-dipping fractures common to both sets of data are: N 85°E, N 60°E, N 40°E, NS–N 15°E, N 15°E, N 15°–20°W, N 40°–50°W, and N 65°–70°W. On the southwestern slope where the above directions are well developed, movements have been predominantly vertical with minor rotation of some blocks. Toward the northern and eastern overthrust mountain front several low-dipping fracture sets appear in addition to the above vertical sets. Interpretations of these patterns in terms of the mechanics of deformation in this mountain range are offered.

CONRAD P. STRAUB, F. J. LUDZACK, G. R. HAGEE, AND A. S. GOLDIN (Robert A. Taft Sanitary Engineering Center, U. S. Public Health Service, Cincinnati, Ohio) *Time-of-Flow Studies, Ottawa River, Lima, Ohio* Chemical (sodium chloride), colorimetric (fluorescein dye), and radioactive (rubidium 86) tracer techniques were used to measure the time of flow of the Ottawa River below Lima, Ohio. This information was desired to permit an estimate of the time required for organic material discharged with the effluents from an activated sludge sewage treatment plant and an industrial plant to reach specific locations downstream. Two runs were made, under low stream-flow conditions, during a two-week period in August, 1956. In the first run fluorescein dye and rubidium tracer were introduced into the stream and measured at two stations downstream, and in the second, dye and radioactive tracers and sodium chloride were introduced and measured at three downstream stations. The results obtained are compared, and a discussion of the equipment needed, the staff required, and the cost of making such a study is presented.

VERNER E. SUOMI (Department of Meteorology, University of Wisconsin, Madison, Wis.) *Power-Spectrum Analysis of Sonic Anemometer Wind and Temperature Measurements* Analog methods of power-spectrum analysis are briefly described. Power spectra of wind components and temperature fluctuations measured with a sonic anemometer-thermometer are described. Power spectra of vertical and horizontal winds as a function of height and stability are given.

GEORGE H. SUTTON, HANS BERCKHEMER, AND JOHN E. NAFE (Lamont Geological Observatory, Columbia University, Palisades, N. Y.) *Physical Aspects of Deep-Sea Sediments* High-frequency sound-velocity profiles were obtained from 26 cores covering a wide range of lithologies and ages (Recent to Miocene).

Density, porosity, median grain size, sorting, carbonate content, and salt content were also measured. The compressional wave velocity in the ocean bottom unconsolidated sediments studied is well represented by

$$V = 2.093 - (0.0414 \pm 0.0051)\phi + (0.00135 \pm 0.00030)\gamma - (0.44 \pm 0.14)\eta$$

where V = sound velocity in km/sec, ϕ = mean grain size in phi units, γ = percentage of HCl soluble material, and η = porosity. Many measurements gave velocities less than the velocity of sound in sea water. Most of the low carbonate samples followed a velocity-porosity relation given by the Wood equation. The regression coefficient, $-0.44\ \eta$, agrees well with the average slope of the Wood equation over the observed porosity range. High carbonate and large median grain size samples gave velocities above that predicted by the Wood equation. These higher velocities are explained as the combined result of a shear strength and low effective porosity in the samples. The highest velocities were found in slowly deposited sediments. Neither degree of sorting nor age were correlatible with velocity. Attenuation was greater in the coarse-grained high velocity sediments than in sediments of smaller grain size.

TARO TAKAHASHI (Department of Geology, Columbia University, New York 27, N. Y.) *Supergene Alteration of Zinc-Lead Deposits* The supergene alteration of zinc-lead deposits and the physico-chemical environment under which such deposits have been altered have been studied. The Goodsprings district, Nevada, was studied as a typical case of supergene alteration in an arid climate; in contrast, the Southern Appalachian and Upper Mississippi Valley districts also studied are in humid climates. Hydrozincite is the principal zinc mineral in the former district, whereas smithsonite and hemimorphite are the major secondary zinc minerals in the Southern Appalachian district, and smithsonite is the predominant secondary zinc mineral in the Upper Mississippi Valley district. Cerussite is the chief secondary lead mineral in the three districts. A paragenetic sequence of the secondary minerals has been established. These observations can be explained by the stability relations of the minerals which were determined by calculations and experiments.

The occurrences of plattnerite (PbO_2) in the Goodsprings district have been interpreted as due to the highly oxidizing environment with probably more than an 0.8-volt oxidation potential, and alkaline solutions with an pH between 7 and 9. The results of spectrochemical analyses indicated that, in supergene facies, the minor elements molybdenum and arsenic came from galena, and vanadium and phosphorus came from the country rocks.

EUGENE A. TAYLOR (U. S. Coast and Geodetic Survey, Washington 25, D. C.) *A New Timing Method for Second-Order Astronomic Longitude Determination* The latest method of observing second-order astronomic longitudes by the Coast and Geodetic Survey is discussed and compared with the previous method. Longitude observations are made on four pairs of east-west stars near the prime vertical, with eight separate pointings on each star. A Wild T-3 theodolite is used to determine the vertical angles, and radio time signals are used directly by the observer for estimating the time of transit of the star image. This eliminates the need for an auxiliary timepiece, and excludes the recorder from the results. Field tests recently conducted at the U. S. Naval Observatory indicate that the probable error of a longitude observed by this method is approximately 0.4 second of arc, which is 0.2 second less than the average probable error of the 'tip' method of timing the observations. These results also show that the observer's personal equation is considerably smaller and more consistent than when the recorder's reaction time enters into the results.

H. C. S. THOM (Office of Climatology, U. S. Weather Bureau, Washington 25, D. C.) *A Time-Interval Distribution for Excessive Rainfall* In present practice, the frequency of excessive rainfall is expressed as *mean* recurrence interval which is a function of rainfall amount for a fixed duration. Since the analytical form of this function is not known, *mean* recurrence interval versus rainfall data must be fitted empirically or non-parametrically. A further difficulty is that a given value of mean recurrence interval does not ensure with a given probability that a rainfall amount will not recur or be exceeded in any given time interval. If the probability is related to recurrence interval (for a fixed rainfall amount and duration) instead of to rainfall amount, the distribution of recurrence interval is obtained and this difficulty is removed. This distribution is parametric and may be mathematically fitted. The distribution theory is developed, and examples are given showing applications to several stations.

AYLMER H. THOMPSON AND C. R. DICKSON (Department of Meteorology, University of Utah, Salt Lake City, Utah) *A Semi-Automatic Micrometeorological Measuring System* This paper describes the instrumental network constructed by the University of Utah, under the sponsorship of the Quartermaster Corps, U. S. Army, for the study of the development and characteristics of temperature inversions in mountainous terrain. Special emphasis is given to the procedure used for directly recording the elements measured. This system is relatively inexpensive and appears to simplify the handling of raw data and the transfer of such data to maps and work sheets. A summary of the results of operation to date is included.

GEORGE A. THOMPSON (Stanford University, Stanford, Calif.) *Gravity Measurements between Hazen and Austin, Nevada* From the pendulum base stations at Truckee and Mystic, California, a line of gravimeter stations, with side loops, was extended eastward through Hazen, Fallon, Eastgate, and Austin, Nevada, crossing the area displaced by faults in 1954. Regionally, the Bouguer anomaly is about -160 mgal from Hazen eastward through Fallon to the Stillwater Range. Farther eastward, the values decrease to -215 mgal near Austin, a change that can be accounted for by isostatic compensation for the increase in average elevation of about 1700 ft. As might be expected, however, the Basin Ranges show no evidence of being individually compensated. Locally, each of the basins has a negative Bouguer anomaly relative to the adjacent ranges, reflecting thick sedimentary fill. Dixie and

Fairview Valleys, in the area displaced by faults in 1954, are characterized by local negative anomalies of more than 20 mgal. This indicates that these valleys contain several thousand feet of lightweight Cenozoic sediments and that their bedrock floor lies close to sea level. The 1954 faults along the west side of Dixie Valley are thus only the latest of many movements that produced not only the visible topographic relief of 5000 ft but also a buried relief of comparable magnitude.

JACK C. THOMPSON (Office of Meteorological Research, U. S. Weather Bureau, Washington, D. C.) *A Generalized Analysis of Forecasting Decisions* Because meteorological predictions cannot, in general, be made with assurance of perfect verification, the weather which is observed following a series of similar forecasts takes the form of a frequency distribution. The nature of such distributions is discussed, and examples are presented. The relationships between the frequency distributions and forecasting decisions are analyzed, and the dependence of conventional measures of forecasting accuracy on both the distributions and the forecasting decisions is pointed out.

L. G. D. THOMPSON (Dominion Observatory, Ottawa, Canada) *An Improved Pendulum Apparatus for Relative Gravity Determinations* A description of a bipendulum apparatus developed by the Dominion Observatory, Canada, for relative gravity measurements is presented. Bronze half-second pendulums are employed in interchangeable pairs and by maintaining essentially identical conditions for all observations the usual corrections to the pendulum periods are held constant. Observed pendulum periods are consistent to 1×10^{-7} sec which corresponds to a gravity measurement accurate to 0.4 mgal.

PHILIP D. THOMPSON (U. S. Air Force, Joint Numerical Weather Prediction Unit, Washington, D. C.) *Numerical Prediction: An Exposition and Review for the Nonspecialist* The present state of numerical weather prediction and recent developments in that field are discussed with reference to general scientific procedure and advances in computing technology. Some of the basic physical concepts and their application to forecasting are described in simple non-mathematical terms. This discussion will be concluded with a brief outline of the probable role of numerical methods in the future practice of weather forecasting.

PHILIP D. THOMPSON (U. S. Air Force, Joint Numerical Weather Prediction Unit, Washington, D. C.) *Uncertainty of Initial State as a Factor in the Predictability of Large-Scale Atmospheric Flow Patterns* This discussion deals with the predictability of the atmosphere or, more exactly, with the gradual growth of 'inherent' errors of prediction, due to errors in an initial state that is reconstructed from measurements at a finite number of points. By investigating the initial time derivatives of the error arising from random analysis error, it is found that the increase of the RMS (root-mean-square) wind error in predictions over periods of a few days depends on: (1) the period of the forecast, (2) the initial RMS vector wind error, (3) the difference between the characteristic scale of the initial error field and the scale of fluctuations in the true initial flow pattern, (4) the area average of the vertical wind shear between 250 and 750 mb, (5) the RMS vector deviation of the wind at about 500 mb from its area average, and (6) the average static stability of the atmosphere. The joint effect of these various factors is given explicitly by a single equation, relating the increase of inherent error to the statistical properties of the initial error field and true initial flow pattern.

In many winter situations, and for initial error fields whose scale is typical of the present observational network, the inherent RMS vector wind error may double its initial value after two days, and rise to the error of sheer guessing in about a week. Doubling the overall density of regular reporting stations would virtually eliminate the increase of inherent error in forecasts over a few days. It is also found that zonally averaged wind fields are inherently more predictable than unaveraged wind fields, at least in cases of predominantly barotropic flow. The results outlined above are interpreted in the terms of a variety of practical and administrative problems, in each of which a dominant factor is the predictability of the atmosphere. Examples are the problems of estimating limits of confidence in forecasts, deciding on the most economical density and distribution of regular reporting stations, fixing the maximum range beyond which detailed 'forecasts' have lost essentially all predictive and economic value and, finally, that of establishing the point of rapidly diminishing returns in the development of more complicated and costly methods of prediction.

G. R. TILTON, G. L. DAVIS, G. W. WETHERILL, AND L. T. ALDRICH (Carnegie Institution of Washington, Washington, D. C.) *Isotopic Ages of Zircon from Granites and Pegmatites* Isotopic lead age determinations have been made on 13 zircons obtained from rocks 185 to 1400 million years old. Concordant or nearly concordant ages are found for all of the samples which contain no detectable common lead, and discordant ages are found for most, if not all, of the samples which contain common lead. A comparison is made between the concordant isotopic age patterns given by three zircons from the Grenville subprovince in Ontario and the discordant patterns given by three zircons from the Cordilleran region of western United States. This indicates that the discordant ages can be related to the recent orogenies which occurred in the Cordilleran region. There is no relation between the agreement of the isotopic ages of zircon and crystal size, amount of radiation damage or optical appearance, that is, zoning, cloudiness, or inclusions. When a discordant age result is compared with the potassium-argon and rubidium-strontium ages of associated mica the Pb^{207}-Pb^{206} age is found to be the closest to the mica age. Isotopic ages are compared with the simpler alpha-lead and chemical lead ages, which do not require isotopic analysis of lead. The non-isotopic ages are approximately correct for zircons which have concordant isotopic ages but are in error when discordant isotopic ages are found. No explanation is offered as to why the mica ages are apparently unaffected by the process or processes which altered the zircon ages. An understanding of this phenomenon would doubtless provide valuable information concerning the post-crystallization history of the samples.

KARL K. TUREKIAN (Department of Geology, Yale University, New Haven, Conn.) *The Significance of Variations in the Strontium Content of Deep-Sea Cores* An Atlantic equatorial eupelagic core, Lamont A180–76, was systematically analyzed for strontium and calcium at 10-cm intervals down the core. The globigerina contribution to the core was found to contain essentially a constant strontium to calcium ratio independent of depth in the core. When the globigerina contribution to the strontium and calcium contents of the core are subtracted, a variation in the strontium to calcium ratio for the fine fraction is observed which is related to the Bricson temperature curve for the core—the high strontium to calcium ratio corresponding to a time of high surface ocean temperature. It is postulated that this sympathetic variation is best explained as the representation of the relative abundance of celestite tests secreted by an Acantharian radiolaria (Odum, 1951). If the carbonate and lutite sedimentation rates are sensibly constant, then Acantharia productivity is temperature dependent. On the other hand, recent work has shown that the rate of sedimentation in the Atlantic equatorial region during the last glacial period was twice as high as the present rate. Since the strontium to calcium ratio of the fine fraction is roughly half as great for glacial time relative to recent times, this may be interpreted as the expression of a constant rate of celestite deposition. If this is the case, a method of chemical geochronometry for continuous, partially dated cores may be conceivable.

O. F. TUTTLE AND C. P. THORNTON (Division of Earth Sciences, Pennsylvania State University, University Park, Pa.) *The Differentiation Index as a Tool for Classifying the Igneous Rocks* The differentiation index (normative Quarz + Albite + Orthoclase + Nepheline + Leucite + Kaliophilite) is a useful and natural quantity for classifying the igneous rocks. It represents the percentage of petrogeny's residual constituents in a rock and is therefore a measure of the 'acidity' or 'basicity' of the rock. A histogram showing the distribution of the differentiation index (DI) in the 5000 analyses in Washington's tables has a maximum at DI = 89, representing the relatively large numbers of analyses of the salic rocks, granites, syenites, and nepheline syenites. In the range *DI* = 80 to 40 (which includes all of the intermediate rocks) the histogram shows no evidence of a minimum which is required by the petrologic maxim that "igneous rocks of the globe belong chiefly to two types: granite and basalt." In fact, the region of the intermediate rocks, that is, *DI* = 80 to 40, is more highly populated than the region of the basaltic rocks, that is, DI = 40 to 20. Volumetrically the intermediate rocks are almost certainly more plentiful than the granites and basalts, as the immense granodiorite batholiths of western North America have compositions that place them in this compositional range. A tentative classification, based on the differentiation index and the silica content, will be proposed for all igneous rocks.

V. DOYLE URBAN, LOWELL P. RIGGS, AND KAZUO WATANABE (Department of Oceanography and Meteorology, Agricultural and Mechanical College of Texas, College Station, Texas) *After-Effects of Squall Lines and Thunderstorms* A case study of squall line conditions is presented in which an evaluation is made of the assumption that moisture lifted to upper levels by squall lines and thunderstorms will exert observable influence over subsequent weather conditions. The methods used for determining the variations of atmospheric moisture distribution and the displacement of air masses at various levels are discussed. The application of synoptic radar observations in this approach to short-range weather forecasting is demonstrated.

R. J. URICK, L. C. PHARO, AND E. SKUDRZYK (Ordnance Research Laboratory, Pennsylvania State University, University Park, Pa.) *A New Method for Measuring the Thermal Microstructure of the Sea* Previous measurements of the small-scale temperature structure of the sea have involved a sensitive thermal device carried through the water by a ship or submarine. The present method permits microthermal measurements to be made from a stationary or slowly drifting vessel by means of temperature elements held in a fixed position along a bar. Nine thermistor beads were spaced at varying distances along a bar 12 ft long, and the temperature difference between successive pairs of elements was measured by means of a bridge circuit and a sensitive d-c amplifier. The records obtained lead to a simple method for determining the correlation function of temperature describing the space distribution of the temperature changes.

A limited number of measurements were made in the waters off Key West, Florida, in conjunction with a field study of the fluctuation of sound transmission in the sea. Within the surface mixed layer, a correlation function of the form $\exp - (r/r_0)$ may be fitted to the data. Better agreement is obtained by assuming two or three functions of the form $\exp - (r/r_0)^2$. The results are in rough agreement with other measurements made off Key West some years ago, and are of the correct order of magnitude to explain the simultaneously observed pulse-to-pulse fluctuation of sound transmission.

H. C. VAUGHAN (Massachusetts Institute of Technology, Round Hill Field Station, South Dartmouth, Mass.) *Meteorological Instrumentation Used by MIT during Project Prairie Grass* Two basic types of meteorological instrumentation were employed during the diffusion experiments. Wind vanes and standard three-cup anemometers of slow response provided measurements of mean wind speed and of variations in azimuth wind direction at a height of two meters; one set of these instruments was located near the release point of the sulfur dioxide, while a second set was located near the center of the sampling network. Five fast-response bivanes, complemented by heated-thermocouple anemometers made of Chromel P and constantan wire, were used to obtain information on the scales and intensities of turbulence. Data were recorded on conventional chart recorders with high-speed drives; frequency response of these instruments was limited to about two cycles per second by the recording apparatus. Auxiliary electronic equipment, recorders, and controls for the remote operation of all meteorological instruments were located in a small van-type truck.

E. H. VESTINE (Rand Corp., 1700 Main St., Santa Monica, Calif.) *The Seasonal Variability in E-Region Winds Responsible for the Solar Daily Magnetic Variation* According to the dynamo theory of the magnetic daily variation, winds flowing within the E-region at a height roughly 100 km generate a world-wide electric current-system at this level. The electric current is generated mainly in middle latitudes by the horizontal motion of electrically conducting air across the radial component of the geomagnetic field. Near the equator the geomagnetic field is horizontal so that the theory predicts that the current above the equator must result from an electrostatic field directed from west to east near noon, closing the current circuit. The theory also predicts that this horizontal electric field must extend to the highly rarefied F-region, which will be lifted bodily upwards in response to the crossed electric and magnetic field. Hence day-to-day differences in middle latitude winds may be reflected, according to the theory, in day-to-day differences in heights and hence in ion densities of the F-region, measured by radio methods. In the present study, effects compatible with these ideas are looked for and found. The day-to-day differences in ionospheric F-region critical frequencies near noon are studied as a measure of corresponding differences in the wind-generated ionospheric electric field at the magnetic equator. These changes in F-region critical frequencies are considered to indicate, at least on an average, corresponding changes in height of the F-region. These changes in height are caused by the electric field of the daily variation. It is shown that the daily variation, though proportional to both the electric field and the electric conductivity, is probably a good indicator of day-to-day changes in wind speeds in the E-region. The data do not support the view that the ionizing solar radiation fluctuates much from one day to the next. This is in accord also with statistical results obtained by Forbush for solar flares and their effects upon the daily variation. The day-to-day changes in wind speed indicated for the E-region in middle latitudes are found to be largest in northern winter, and least in northern summer, and are discussed in relation to evidences of variability dependent on season noted from meteorology for tropospheric winds. Changes in wind speed with sunspot cycle are also discussed.

The average magnitude of the daily magnetic variation shows a high correlation with sunspots (as high as 0.99 for yearly averages). Thus, having eliminated electric conductivity of the E-region as an important cause of the day-to-day variability in the magnetic variation, the wind speed in the E-region must be able to change by a factor of two or more from one day to the next as a consequence of solar events.

B. VONNEGUT (Arthur D. Little, Inc., Cambridge, Mass.) AND BERTON M. ATKINSON (University of Minnesota, Minneapolis, Minn.) *Time-Lapse Motion-Picture Photography Looking from High-Altitude Balloons* Techniques are described for making time-lapse motion pictures of clouds and weather systems from high-altitude balloons. Preliminary results show that this is a promising tool for investigating cloud circulation and their development. A movie of some preliminary flights is shown.

B. VONNEGUT, C. B. MOORE, AND D. F. COMSTOCK (Arthur D. Little, Inc., Cambridge, Mass.) *Observations of the Electrification of Cumulus Clouds* Airplane measurements of the electric fields on the outside of cumulus clouds, and special radiosonde measurements of the reversal of the fair-weather electric field inside small thunderstorms, using captive balloons, are described. In the latter cases, electric field reversals were observed in a number of the clouds before any echo was detectable with an X-band radar. These findings suggest that either the electrification was caused by precipitation particles too small to be detected by the radar or that the electrification occurred before the formation of the precipitation elements. Further work is in progress.

A. JAMES WAGNER (Department of Meteorology, Massachusetts Institute of Technology, Cambridge, Mass.) *Mean Temperature from 1000 to 500 mb as a Predictor of Precipitation Type* The frequency of occurrence of frozen precipitation forms relative to the frequency of occurrence of non-frozen forms is determined as a function of the mean temperature (or thickness) of the layer from 1000 mb to 500 mb. The results are derived from the data for a large number of stations in the United States during two winter seasons. A map of the thickness values for equal probability of occurrence of frozen and nonfrozen forms illustrates the effects of altitude and continentality. It is found that the form of the precipitation can be specified with a confidence of 75 pct or more when the thickness value at a station is 100 ft or more from its 'equal probability' value. Some refinements of the technique are discussed.

NORMAN K. WAGNER (Electrical Engineering Research Laboratory, University of Texas, Austin, Texas) *A Description of a Micrometeorological and Oceanographic Measurement Program in Conjunction with Radio Propagation Tests over the Gulf of Mexico* In the spring of 1955 an over-water measurement program was conducted by the Electrical Engineering Research Laboratory of the University of Texas about 35 mi off the coast of Louisiana on two oil-drilling platforms in the Gulf of Mexico. A series of micrometeorological and oceanographic measurements was taken in conjunction with radio propagation tests. The program was designed so that the resulting meteorological data would: (1) help the radio engineer to determine which atmospheric and sea surface variables affect the reflection of radio signals, and (2) be of interest from a strictly micrometeorological standpoint. Meteorological data were obtained with a number of instruments ranging from standard three-cup anemometers to the Crain microwave refractometer. Gulf wave heights were measured with a step gage, while the longer period variations were obtained by means of a surf-beat gage designed and built at the Applied Physics Laboratory of Johns Hopkins University. The meteorological and oceanographic aspects of these experiments are discussed, including a description of the instrumentation, the data obtained, and the data processing techniques employed. In addition, some of the more interesting results of this study are presented.

MATT WALTON (Yale University, New Haven, Conn.) *On the Logic of Geology* The 'geology' of a region is known if the content and state of the geologic materials in the region, the configuration of the structural components of the materials, and the sequence and nature of the processes that have affected the materials are known. The investigative operations of geology seek this information, which falls into two operationally different classes: (1) information on content, configuration, and state (represented by the symbol *C*), (2) information on processes (represented by *P*). Information on sequence is dependent on the relationship of configuration to time-dependent processes, and if *S* is taken to mean the possible sequential arrays of past configurations and processes, then 'geology' may be stated operationally as

$$S = f(C, P)$$

which may be called 'the geologic equation.'

Operations seeking *C* include mapping, collecting, classifying, and pegrographic, mineralogical, and chemical analysis. Operations seeking *P* involve experimental investigation or direct observation of natural processes. Some interpretive operations involve the nature of the function. The doctrine of uniformitarianism, generally regarded as the philosophical foundation of geology, plays a special role in the equation. It defines our uniquely 'geological' means of investigating process *P* and states a functional relationship between process *P* and configuration *C*. The equation will prove useful in testing the validity of geological arguments and clarifying geological terminology.

WILFORD F. WEEKS (Air Force Cambridge Research Center, Bedford, Mass.) AND OWEN S. LEE (U. S. Navy Hydrographic Office, Washington 25, D. C.) *Observations on the Growth of Sea Ice at Hopedale, Labrador* A layer of slush commonly forms in the lower part of the snow cover on top of sea ice after periods of near-freezing air temperatures. This slush layer is caused by the migration of intragranular brine from the sea ice upward into the snow under hydrostatic pressure resulting from the depression of the ice sheet by the weight of the snow. Plots of the variation of snow and slush density with time are presented. The top of the slush layer is in general above the theoretical water level showing that capillary action is an important factor in determining the thickness of the layer. Freezing of the slush forms an equigranular fine-grained ice with a pronounced vertical C-axis orientation and causes irregularities in plots of the average salinity of the ice sheet and accumulated degree-days of cold against the thickness of the ice sheet. After two periods of slush formation an extreme scatter develops in the ice thickness with the maximum ice thickness occurring beneath deep snow drifts. The resulting ice thickness is 15 pct greater than would be expected from projecting known sea-ice growth curves.

G. W. WETHERILL, G. L. DAVIS, AND L. T. ALDRICH (Carnegie Institution of Washington, Washington 15, D. C.) *Age Measurements on Rocks North of Lake Huron* Previous work has shown that absolute ages of rocks may be found by application of the potassium-argon and rubidium-strontium methods to mica. This work is being extended to include Precambrian rocks in the Huronian area of the Canadian Shield as shown in Table 1.

In contrast to earlier work, the Rb-Sr and K-A ages are not in good agreement for most of the samples. Particularly anomalous are the two cases in which the K-A ages are much higher than the Rb-Sr ages. Although the interpretation of these data is complicated by this fact, they appear to indicate an episode of mineralization in this area 1350 million years ago.

TABLE 1

Rock	Mineral	*Rb-Sr* age my	*K-A* age my
Hearst pegmatite	Lepidolite	2595	2605
Wavy Lake Granite	Biotite	1075	1025
Cutler Batholith			
Granite	Biotite	1325	1380
Pegmatite 1	Muscovite	1760	1420
Pegmatite 2	Muscovite	1750	1350
Copper Cliff Rhyolite	Muscovite	1700	1400
	Biotite	1220	2110
Levack Novite	Biotite	1830	
Sudbury Gabbro	Biotite	1350	1830

FRED L. WHIPPLE AND GERHARD F. SCHILLING (Smithsonian Astrophysical Observatory, Cambridge, Mass.) *Upper Atmosphere Data Expected from the IGY Satellite Tracking Program* A brief introduction describes the presently planned three phases of the IGY satellite tracking program: Minitrack, Photographic Observations, and Moonwatch. The complementary objectives of each phase are outlined and the respective contributions, expected with regard to meteorological parameters of the upper atmosphere, are discussed in detail. Tracking provides high-altitude values of air density and drag, reflecting long-cycle variations, day-night effects, possible tidal components, and more detailed data. Differences in orbital positions as given by optical versus radio observations should provide data on the electron concentration in the ionospheric regions. Our present knowledge of atmospheric parameters at high altitude is so limited that the first satellites will provide important results for the planning of future satellite research vehicles. They will also serve as the basis for evaluation and calibration of data obtained to date from such fields of study as meteor observations, rocket research, and ground-based probing of the ionosphere.

W. A. WHITE AND GEORGE B. MAXEY (Illinois State Geological Survey, Urbana, Ill.) *A Possible Mechanism for the Concentration of Brines* A possible explanation for the underground concentration of brines may be that shales act as a semi-permeable membrane that allows water to pass through but is impermeable to passage of salts. This may be the primary mechanism for formation of brines in isolated basins, and for concentration of dissolved salts in aquifers where brines form under other conditions.

H. G. Wilm (State University College of Forestry, Syracuse 10, N. Y.) *Water-Yield Improvement in Arizona* The development of cities and irrigated agriculture, the depletion of ground-water supplies, and a series of dry years have caused an acute water shortage in southern and central Arizona. In efforts to find at least a partial solution for these shortages, the University of Arizona made an appraisal of possible means for increasing water yields through the management of Arizona watersheds, especially in the Salt River valley area. Through direct examination of the resources of vegetation, soil, and water and the advice of numerous consultants, it has been concluded that substantial improvements in water yield can be obtained by the management of forest vegetation. Particular benefits are expected from the control of water use by phreatophytes and by reducing the density of forest cover in areas at the higher altitudes in the Salt River valley watershed, particularly the upper ponderosa pine, pine-fir, and spruce-fir types. Smaller benefits, if any, can be expected from the manipulation of the drier forest areas such as pinon juniper and low-altitude brush areas.

Walter H. Wischmeier (Agricultural Research Service, Lafayette, Ind.) and Dwight D. Smith (Agricultural Research Service, Beltsville, Md.) *Kinetic Energy of Rainfall and Its Relationship to Erosion Losses* The paper discusses computation of the kinetic energy of a rainstorm and the significance of such an evaluation of a storm in a soil loss prediction equation. An equation is developed for simple computation of total rainfall energy of a storm from the information on a recording raingage chart. The effects of energy and its interaction with other rainfall characteristics on soil loss are evaluated in multiple regression equations for plot data on several soil types. This information is applied in a suggested method for removal of the effect of rainfall differences from plot and small watershed data. Adjustment of soil losses for differences in rainfall characteristics permits comparison of management practices on plots not subjected to identical rainstorms and thereby greatly enhances the value of currently available soil-loss data.

John A. Wood, Jr. (Massachusetts Institute of Technology, Cambridge, Mass.) *The Solubility of Quartz in Water at High Temperatures and Pressures* A theoretical equation for the solubility of quartz in supercritical water is set up, the chemical potentials of the participating components being evaluated by methods of statistical mechanics. The equation is fitted to the experimental quartz solubility data of G. C. Kennedy, which extends up to 570°C and 1750 bars. Although the solution mechanism is indeterminate, it is seen that complex, hydrated molecules (probably polymers of H_4SiO_4) are involved at pressures greater than about 500 bars. These molecules dissociate at lower pressures, and further polymerize at higher pressures.

The solubility equation is fitted to one particular solution mechanism, which holds only along a single isovolumetric curve in the (T, Conc.) plot. This same equation is applied at higher and lower volumes, and is seen to closely approximate the experimentally determined solubility of quartz over a wide (P, T) range, failing only in regions of high pressure-low temperature and low pressure-high temperature. Solubility curves are extrapolated to 800°C and 2500 bars, the solubility of quartz reaching 1.7 pct by weight at this extreme value.

J. Lamar Worzel (Lamont Geological Observatory, Columbia University, Palisades, N. Y.) *Tests of Graf Sea Gravimeter* Fifty-nine simultaneous gravity observations were made with the Graf sea gravimeter and the Vening Meinesz pendulums on board USS *Becuna* (SS 319) between Palma, Mallorca, and Portsmouth, England. A wide variety of weather conditions was encountered.

The Graf sea gravimeter was not yet equipped with apparatus to correct for the second-order horizontal accelerations. The observations for both instruments were corrected in the appropriate ways except for the Eötvos effect, the depth of submergence, and the horizontal second-order corrections. The dial calibration and the drift corrections for the Graf meter were not well established before these tests. A straight line was drawn through the data of the differences between the two instruments plotted against observation time. All readings of the Graf meter were corrected by an amount determined from the straight line to take care of the dial calibrations and the drift. The resultant differences between the two instruments showed a close approach to a statistical distribution. Three observations showed differences in excess of nine mgals, probably due to bad depth control. Four observations had differences between six and nine mgals, 13 had differences between three and six mgals, and 39 had differences between zero and three mgals.

These tests show that the Graf sea gravimeter has great promise. The drift characteristics of the meter must be improved, and better dial calibration achieved. An apparatus to take account of the second-order horizontal accelerations must be added. Many more comparisons with the Vening Meinesz apparatus must be made before the latter can be displaced. The gravimeter is much less bulky, much less fragile, and presents data in a form much easier to reduce to gravity values. If the meter could be operated on a stabilized platform, it is probable that observations could be made on a surface ship at least in weather up to state 4.

R. E. Wyett, M. G. Talcott, and P. P. Starke (Observations and Station Facilities Division, U. S. Weather Bureau, Washington, D. C.) *Recent Developments in the Weather Bureau's Surface Observational Program* Recent developments in this field, including such things as end-of-runway ceiling and visibility programs, the use of remote reading equipment, automatic and mobile weather stations, standardization of surface wind measuring techniques, special observations for the IGY and major changes in coding and reporting procedures, including observational requirements for the 'jet age,' are discussed.

P. J. Wyllie and O. F. Tuttle (Department of Geophysics and Geochemistry, Division of Earth Sciences, Pennsylvania State University, University Park, Pa.) *The Effect of Volatile Materials on the*

Melting Temperatures of Silicates This study was undertaken to investigate the melting relations in silicate systems in which volatile materials are present in addition to water. Results have been obtained on the beginning of melting in the following systems: albite-CO_2-H_2O, albite-HCl-H_2O, albite-NE_0-H_2O, albite-NH_3-H_2O, albite$_{70}$ orthoclase$_{30}$-CO_2-H_2O, granite (Westerly, R. I.)-CO_2-H_2O, granite-HCl-H_2O, and granite-HF-H_2O. The silicates begin to melt at higher temperatures in the presence of CO_2 and NH_3 solutions than in the presence of water vapor alone, but low concentrations of HF in the volatile phase produce marked lowering of melting temperatures compared to that produced by water vapor. The effect of HCl is complicated by chemical reaction with the silicates and the formation of a liquid phase by solution of HCl in the silicate cannot yet be distinguished from the formation of a liquid phase by mutual fluxing between the products of the reaction. The importance of mineralizers in the processes of formation and alteration of rocks is well known and it appears that distinction must be made between those volatiles which react with the silicates to form new minerals and those which act simply as a flux. Granite begins to melt at 610°C in the presence of a 4 weight per cent solution of HF at a pressure of 40,000 lb/in^2, suggesting that small concentrations of HF in magmatic systems may be very effective in lowering the temperatures of crystallization of the magmas.

ALFRED ZMUDA (Applied Physics Laboratory, Johns Hopkins University, Silver Spring, Md.) AND JOHN MCCLAY (Air Force Cambridge Research Center, Bedford, Mass.) *Preliminary Results of Extrapolation of Geomagnetic Field Components to the Boundary of the Earth's Core* A previously reported method (A. Zmuda and L. McClung, *Trans. Amer. Geophys. Union*, v. 36, pp. 939–942, 1955; A. Zmuda, *Trans. Amer. Geophys. Union*, v. 37, pp. 9–12, 1956) of extrapolating geomagnetic elements was used to compute the values of the components of the intensity at the boundary of the Earth's core. In the method, each component is separately continued by a Taylor series in which the derivatives in the vertical direction are obtained from surface data on the components. The rapidity of convergence of the series depends on the extrapolation distance and the type of field being extrapolated. Calculations were made with surface data taken over various regions of the Earth, and the results are encouraging. Approximately four terms of the series must be computed for the extrapolation of each surface value to the boundary of the core.

Abstracts of the papers presented at the Pacific Southwest Regional Meeting, Sacramento, California, February 14–15, 1957 listed in the order of the last name of the first author

H. W. ANDERSON (U. S. Forest Service, California Forest and Range Experiment Station, Berkeley, California) *'Operation Wet-Blanket' Gets under Way.* Research in snow-pack management, termed by the late E. A. Colman, 'Operation Wet-Blanket,' has gotten under way. The Central Sierra Snow Laboratory near Donner Summit has been reopened. This laboratory was operated from 1946 to 1952 as part of the Cooperative Snow Investigations. Now, additional basic studies of snow physics and forest hydrology are being conducted there. In the southern Sierra, at the Teakettle Experimental Watersheds, preparation for testing the hydrologic effects of logging are being made. Stream gaging was renewed last September for five experimental watersheds inoperative since 1941. The reservoirs which had accumulated sediments since 1938 were cleaned out. Sedimentation of those reservoirs had been measured periodically since 1938. These sediment data have been analyzed to provide a method for correction of measured sediment for the trap efficiency of the reservoirs. Meteorological and snow evaporation measurements in the area are being obtained with the cooperation of the PG & E Company, which is also servicing the Teakettle gaging stations during the winter. Another set of experimental watersheds at the headwaters of the American River are in a preliminary stage of testing before the installation of gaging equipment. In seven of these watersheds maximum stage and staff gages have been installed at control sections. This cooperative snow management research is being conducted by the U. S. Forest Service, California Forest and Range Experiment Station, in cooperation with the State of California, Department of Water Resources. The research began in the summer of 1956 and has been programmed for the next five years.

H. FRED ARLE (Weed Investigations Section, Agricultural Research Service, Phoenix, Arizona) *A Summary of Results of Experiments and Field Trials Pertaining to the Control of Salt Cedar (Tamarix gallica).* Numerous experiments and trials to control salt cedar (*Tamarix gallica*) have been conducted by various federal and state agencies during the past nine years. These studies have been conducted to evaluate various chemicals and mechanical operations as a possible means of controlling salt cedar. Different formulations of 2,4-dichlorophenoxyacetic acid and related materials have been applied by aerial and ground spray equipment. In almost all cases, the initial effects of these treatments have appeared favorable, defoliation is rapid and is followed by the death of twig and stem extremities. Plant recovery, however, is usually started within several weeks as indicated by the appearance of new shoots and foliage. Retreatment has provided additional temporary control but very little actual reduction in salt cedar population. There is evidence to indicate that many applications have involved noneffective formulations of 2,4-D or insufficient rate of application for maximum effect. Control of salt cedar by mechanical means has been attempted on a considerable acreage in New Mexico. In some instances

permanent clearing was accomplished and the cleared land put to agricultural use. More often it has been found necessary to repeat mechanical operations from one to three times per year to control seedlings and regrowth. Best control of salt cedar has been obtained when applications of 2,4-D or related materials are made to young regrowth, which follows initial mechanical removal of old growth.

V. S. Aronovici (U. S. Agricultural Research Service, Pomona, California) *Influence of Buffer Ponds upon Cylinder Infiltrometer Flow Patterns under Moist Soil Conditions.* The influence of buffer ponds upon the water-flow pattern from a cylinder infiltrometer under near saturated conditions is graphically demonstrated by model studies. These observations clearly illustrate the importance of buffering in securing reliable long-term infiltration data. Methods of using dye patterns, and a technique of maintaining a slight suction at the base of the model are described. Small tensiometers have been used to observe the hydraulic gradients within the model during observation.

Robert T. Bean, Raymond C. Richter, and Cole R. McClure (California Department of Water Resources, Sacramento, California) *Ground Water Resources of California.* Ground water occurs in 250 ground-water basins in California. The areas considered as basins are largely or entirely valley land, each valley floor area containing a minimum of about five square miles. The simplest type of basin consists of Quaternary and late Tertiary valley fill surrounded and underlain by nonwater-bearing rock. In more complex basins, the water-bearing sediments or volcanics, or both, underlying the valley floor area extend in part into the surrounding highlands. Other types of basins exist. Estimates of storage capacity within certain depth limits are available for 211 basins comprising 96 pct of the total valley floor area of basins in the State. Their aggregate storage capacity is about 450,000,000 ac ft. Usable storage capacity for 80 basins comprising 43 pct of the total area is estimated at about 120,000,000 ac ft. Overdraft is known to exist in at least 33 ground-water basins. At least six adverse conditions occur in overdrawn basins. Sea-water intrusion has caused extensive damage in nine basins, and may have degraded ground waters in an additional 70 small coastal areas. Substantial land subsidence is occurring in Santa Clara and San Joaquin Valleys. Other adverse effects include: intrusion of saline connate waters, adverse salt balance, interchange of aquifer waters, and increased well development costs.

C. H. Becker and J. L. Soske (Department of Geophysics, Stanford University, Stanford, California) *Stereoseismic Exploration.* Stereoseismic exploration is a new and improved system of employing the principles of the reflection seismograph. The technique is proposed as an aid for solving the more difficult structural problems in the Earth sciences. Improvements result from using a high density of undistorted seismic data. General areas of improvement are: (1) the substitution of a three-dimensional approach for the more commonly used two dimensions, (2) the increase of the quantity of data to represent all necessary details of the spatial form and attitude of the reflected wave fronts which emerge at the surface of the ground; (3) the preservation of the essential relationships of frequencies, phases, amplitudes, intensities and dispersion effects of the reflected waves, (4) the employment of modern high-density data processing methods to record, store and read out the reflected wave information, and (5) the transfer of the stored information to video circuits and thence to a specially designed type of calibrated television screen for direct analysis. The method of analysis is derived from the principle of multiple-channel stereophonic detecting and recording. The acoustical reception is transformed instantaneously into a logarithmetic scale of intensity and then the reflected acoustical events of three dimensions are rectified and compared for phase shift variations. The stereoseismic pattern is produced on a television screen by presenting the pressure wave distribution at the ground surface as Newton's rings of equal wave inclination.

Harry F. Blaney (U. S. Agricultural Research Service, Los Angeles, California) *Relationship of Pan Evaporation to Evapotranspiration by Phreatophytes and Hydrophytes.* Evaporation from pans has been used for many years in connection with water-supply studies to estimate evapotranspiration by water-loving vegetation. Usually Weather Bureau pan records have been employed for this purpose, although in some instances evaporation from atmometers or evaporimeters have been used. This paper presents data observed in the Pacific Southwest on pan evaporation and evapotranspiration by salt grass, salt cedar, tules, and other vegetation. Water consumption by these two important factors in the hydrologic cycle are compared and their ratios determined for the purpose of estimating evapotranspiration from evaporation pan records for areas where no water use measurements are available.

Curtis W. Bowser (U.S. Bureau of Reclamation, Boulder City, Nevada) *Introduction and Spread of the Undesirable Tamarisks in the Pacific Southwestern Section of the United States and Comments Concerning the Plants' Influence upon the Indigenous Vegetation.* The Tamaricaceae family is a relatively small group of plants comprised of four genera all indigenous to Africa, Europe, and Asia. Only members of the genus *Tamarix* are found abundantly in the United States and of these the species *T. gallica*, commonly called salt cedar, has become so adapted and grows so vigorously that it has infested many natural drainage channels and waste areas. The history of *Tamarix* spp. introduction into North America is not on firm record. Possibly specimen plants were brought in by the early explorers, or later by exchange of plants between horticulturists. Regardless of the date that the plants were introduced, their spread since the year 1900 has been phenomenal which has resulted in a gradual transition of the characteristic endemic willow, poplar, arrowweed, baccharis communities to that of almost pure salt cedar in many drainage systems throughout the Southwestern section of the United States. The tamarisk plants, in addition to creating a hazard by con-

gesting in the natural drainage ways thereby creating a flood problem, also consume large quantities of water in a non-beneficial manner. The usefulness of salt cedar for soil erosion control, wildlife habitat, or wood and pulp products is extremely limited. At elevations above 4000 ft, and in the Pacific Northwest, the species is not gaining a strong foothold and does not appear to have the ability to spread with rapidity so characteristic of plants at lower elevations in the Southwest. Nevertheless, there are reports of the species growing at elevations from 9000 to 11,000 ft above sea level, and as the plant has escaped cultivation from coast to coast, it clearly indicates that tamarisks eventually will become distributed and possibly will be regarded as an objectionable species in many of the natural drainage ways throughout North America.

FRANK B. CLENDENEN (Department of Engineering, University of California, Berkeley, California) *Water Resources Development by Conjunctive Operation of Surface and Ground-Water Reservoirs.* The recent tremendous population increase in California is responsible for many water problems. This population growth is predicted to continue far into the future. Therefore, the problems of today will be small relative to those that will develop in the future if definite action is not taken to insure the establishment of adequate water supplies. Reservoirs, the basic tool in water-resources development, cannot be economically constructed at any location and to any capacity, in fact, surveys indicate that the total present and future surface reservoir storage capacity within California is considerably less than that which will be required for full economic development. Such full development of California's economy will require extensive utilization of ground-water storage capacity. In order to gain maximum efficiency in water-resources development, surface- and ground-water reservoirs should be conjunctively operated. Such operation is based on maximizing the total net benefits of a project without regard to maintaining rigidities of operation of individual features. Therefore, if water conservation is the chief purpose of a project, firm yield of both surface and subsurface reservoirs conjunctively operated would be sought and such operation would usually significantly reduce the firm yield of the surface storage below that obtainable by separate operation. Generally the effect of conjunctive operation on flood control and conservation is positive while hydroelectric power generation and recreational use of reservoirs is adversely affected. As an illustration of the function of the basic features of a conjunctively operated water-resources development, the plan for ultimate development of the American River basin is presented.

HENRY J. CREMER (U. S. Corps of Engineers, Los Angeles, California) *Eradication and Control of Phreatophytes, and Replacement of Ground Cover.* Increasing agricultural water requirements and prolonged droughts have highlighted the necessity for considering all possible methods of water conservation. One of the newer conservation practices, about which there still remains much to be learned, is that of eliminating phreatophytic growth along water courses and in reservoirs. These noxious plants rob the ground water basins of large quantities of water by transpiration. The problems attendant upon controlling phreatophytic growths and of replacement plantings to deter infestation are being studied in several phreatophyte-infested areas. Both mechanical and chemical methods of phreatophyte control are being used with varying degrees of success. The phreatophyte problem cannot be solved simply and must involve a long-range program of planned inhibition until phreatophyte growth in infested areas is controlled and beneficial replacement plantings have been established.

G. H. DAVIS (Ground Water Branch, U. S. Geological Survey, Sacramento, California) *Configuration of the Base of the Principal Body of Fresh Water in the Sacramento Valley, California.* Interpretation of more than 250 electric logs, chiefly exploratory test holes for gas, indicates that deposits containing fresh water extend to depths ranging from a few hundred feet along the flanks of the Sacramento Valley to more than 3000 ft in the southwestern part of the valley. In much of the valley the base of the fresh water represents a stratigraphic horizon, the boundary between continental and marine deposits. Locally, however, marine deposits have been flushed of connate water and in some areas continental deposits contain saline water. In places the change from fresh water to saline marine water is transitional through an interval of several hundred feet. In a general way the base of the fresh-water body delineates several of the important geologic structures of the valley, including (1) the synclinal axis of the Sacramento Valley, which lies far west of the geographic and surface-drainage axis, (2) the Dunnigan Hills-Plainfield Ridge anticline, (3) a syncline between the Dunnigan Hills-Plainfield Ridge anticline and the Coast Ranges, (4) the Montezuma Hills, and (5) Sutter Buttes. Bodies of saline water not related to known geologic structures occur at shallow depth south of Sacramento, west of Sutter Buttes, and south of Sutter Buttes.

JOHN P. DECKER AND JANET D. WIEN (Rocky Mountain Forest and Range Experiment Station, U. S. Forest Service, Tempe, Arizona) *Time Course Studies of Transpiration of Tamarisk and Eucalyptus.* In a study of transpiration of phreatophytes, an apparatus was developed that recorded directly and continuously the transpiration rate of a single intact leaf or twig. A leaf was sealed in an illuminated, constant-temperature glass chamber that was ventilated at a known rate with dry air. The absolute humidity of the air flowing out from the chamber was recorded continuously by an infrared gas analyzer, and this could be related directly to transpiration rate. Transpiration increased smoothly to a new constant rate when a leaf was illuminated, and it decreased smoothly when the leaf was darkened. When a twig or petiole was severed in air, transpiration accelerated briefly in a smooth surge then came to a gradual stop. When a petiole was severed under water, transpiration slowed to a new constant rate. It surged briefly when the cut end

was then exposed to air. A tentative explanation can be offered: the vascular system of a transpiring plant is under hydraulic tension; when the petiole is cut, tension is released as air intrudes into the severed vessels and the leaf has a momentarily increased water supply; when the petiole is cut under water, water does not intrude freely because the ends of the vessel are crushed and frayed, thus water supply to the leaf is somewhat reduced; when the cut end is then exposed, air intrudes freely where water could not.

C. E. Jacob (1926 South Columbia Lane, Orem, Utah) *Full Utilization of Coastal Groundwater Reservoirs.* Coastal groundwater reservoirs are classified as confined, unconfined, and mixed reservoirs, also according to direction of dip, whether landward or seaward. The consequences of the basic law, inflow equals outflow plus storage gain, are examined in several cases and illustrated from actual histories, with various distributions of the three basic items. Inflow includes natural inflow of fresh water, artificially induced inflow of sea water, artificial recharge of fresh water, and injection of sea water through wells. Outflow includes natural outflow to sea and discharge of wells. In confined reservoirs storage derived from lowering of head is very small; in unconfined reservoirs, much larger; and in both confined and unconfined ones the effective storage from replacing fresh water by sea water is still larger; the ratios among these three being roughly 0.0001 : 1 : 40. Accordingly induced encroachment under close control will often permit maximum withdrawals from storage compatible with safety and long-range economy, especially in confined reservoirs. The great waste of leakage of coastal reservoirs to the sea should be stopped by operating them as near empty of fresh water (or as near full of sea water) as feasible. In the first stage of their development reservoirs are fully utilized generally by (1) drawing heavily upon natural storage and (2) diminishing natural outflow to sea. Because of close inverse relationship between rate of natural outflow and column of intruding wedge of sea water, both ends are accomplished simultaneously. The optimum size of wedge is dictated by practical considerations. However, it may be desirable to hasten its growth at first by injecting sea water through wells. During later stages of development, with natural outflow still held to a practical minimum, the further deficit may be met most effectively by recharging through wells or by water spreading. The relative merits of injected fresh-water barriers to halt encroachment are considered.

Miroslav V. Jiranek (International Engineering Co., Inc., 74 New Montgomery Street, San Francisco, California) *Flow through Granular Media.* The flow of water through a granular media is discussed with a suggested laboratory method used by the author to determine the filtration law on undisturbed soil samples within a desired range of the slope by one single experiment. This method is compared with existing field and laboratory procedures to illustrate the feasibility of a single, rapid and direct experiment to obtain the filtration law directly assuming a nonlinear relationship between velocity and slope. A description of the apparatus developed by the author to obtain a function of head versus time is submitted with a numerical and graphical transformation of this result to a function of velocity versus slope. Both a linear and nonlinear relationship between velocity and slope are presented for the determination of the filtration law. Possibility of using undisturbed samples tested for permeability for other physical properties before and after filtration experiments is stressed. Experiences with this equipment is the basis of preliminary conclusions from the experimental results.

Raphael G. Kazmann (419 West Seventh Street, Stuttgart, Arkansas) *Problems Encountered in the Utilization of Ground-Water Reservoirs.* Ground-water reservoirs are compared to surface-water reservoirs and the similarities and differences are pinpointed. For example, the boundaries and storage capacity of a water-bearing formation are not readily determinable. By comparison, an aerial survey of a potential reservoir site, from which a contour map may be prepared, is generally sufficient to determine the boundaries and storage capacity of any desired impoundment. Further, ground-water reservoirs are full to start with, whereas the area of an impoundment is usually devoid of water, except for a small amount contained in the river channel. Such differences, and others discussed in the body of the paper, give rise to social and engineering problems which are not duplicated elsewhere in the field of water-resource development. It may not be an exaggeration to state that, at our present level of technique and knowledge, the scientific and engineering problems are less vexing than the problems which must be solved by negotiation and persuasion. Examples of problems encountered in the utilization of ground-water reservoirs are cited. As case histories, problems of industrial ground-water supply in the East St. Louis area, and of municipal ground-water supply in the Canton, Ohio, area are discussed.

Ben E. Lofgren (Ground Water Branch, U. S. Geological Survey, Sacramento, California) *Ground-Water Circulation in Deep Wells on the West Side of San Joaquin Valley, California.* Accelerated withdrawal of water from deep irrigation wells along the west side of the San Joaquin Valley has substantially modified the pattern of ground-water movement in the underground reservoir. The artesian head in the deeper aquifers has been drawn down locally as much as 300 ft. Downward head differentials of more than 100 ft, between the upper water-table aquifers and the lower confined aquifer, exist in more than 1200 sq mi on the valley's west side. Large but undetermined quantities of ground water circulate downward through the confining clay layer that separates these two extensive bodies of ground water and through the casings of many hundreds of active and abandoned wells in the area. Measurements of the rate of downward interaquifer circulation in wells, and the depths at which the water enters and leaves the well casing, were made in 30 idle irrigation wells. An Au-type deep-well cur-

rent meter was used in the study, after calibrating the meter in a specially built model flowing well. In the range of low-water velocities encountered in the field, the characteristic curve of the Au-type current meter varies considerably. At water velocities between 0.5 and 12.0 ft per sec, however, the meter constant as determined in the laboratory follows roughly a straight line. Water-velocity measurements were made in wells to depths of 1400 ft, and downward flows of as much as 1.1 cfs were encountered. In most wells tested, water enters the casing through casing breaks above the clay confining layer, moves downward at rates ranging from 0.1 to 0.6 ft per sec, and dissipates into the deep aquifers through perforations in the casing. No estimate has been made of the rate of ground-water circulation that takes place in the gravel envelope around each well casing.

JOHN F. MANN, JR. (University of Southern California, Los Angeles, California) *Development and Management of Fractured-Rock Aquifers.* Most of our effort in California has been directed toward a study of aquifers of alluvial origin. As these aquifers in many areas are approaching or have passed full safe utilization, we should perhaps give more thorough consideration to developing aquifers of nonsedimentary types. Large areas in California are underlain by basement rocks—plutonic and metamorphic rocks which can contain water only where fractured. Prospecting for water in fractured rocks is extremely difficult; often the entire yield of a well is derived from a single fracture less than an inch wide. Rarely is a fracture located directly on the ground and there recognized as being distinctly favorable. Aerial photographs can be of tremendous help where the mantle is thin, patchy, or absent. Where the mantle is thicker no surface geologic method is effective, and geophysical prospecting may be the only successful technique. Drilling in basement rocks is very expensive, the percentage success is relatively low, and consequently more *test* drilling can be justified. Modifications of drilling technique will sometimes improve the chances of success. Development of fractured rock aquifers should proceed more cautiously than for alluvial aquifers. High permeability coupled with low overall porosity encourages overpumping.

VICTOR MOCKUS (U. S. Soil Conservation Service, Beltsville, Maryland) *Use of Storm and Watershed Characteristics in Synthetic Hydrograph Analysis and Application.* A rational analysis of unit hydrograph relations gives the peak rate equation $q_p = (KAQ)/T_p$, with q_p = peak rate in cfs, K = a constant later shown to be 484, A = drainage area in square miles, Q = runoff volume in inches, and T_p = time in hours from beginning of rise to peak rate. The relation of T_p to storm duration (D) and watershed or basic lag (L) is $T_p = (D/2) + L$. Historical usage of the peak-rate equation is shown by reductions to its form of such equations as Snyder's system of equations, the Rational Method, the Armco Rational Method, and others. As the underlying principle of those equations, the peak rate equation serves to explain their differences and limitations, and to give physical significance to their empirical constants. A dimensionless hydrograph is given and used with the peak rate equation in an example of synthetic unit hydrograph construction. Expansion of this method to simplify hydrograph construction for complex storms and watersheds is outlined. The effects of channel seepage losses and of subsurface flow accretions on both the empirical derivation of unit hydrographs and the use of any synthetic hydrograph are indicated. The peak rate equation is used to develop a differential equation. The general solution is given and its practical significance discussed.

J. F. POLAND AND J. H. GREEN (Ground Water Branch, U. S. Geological Survey, Sacramento, California) *Subsidence in the Santa Clara Valley, California—A Progress Report.* Subsidence of the land surface in the Santa Clara Valley, Santa Clara County, California, has been observed since 1933. A network covering the subsidence area was first leveled in 1934. That network was releveled seven times between 1935 and 1940, inclusive, again in 1948 and 1954, and in part in 1956, all by the United States Coast and Geodetic Survey. The releveling of the network in 1954 indicated that subsidence of the land surface had reached 7.75 ft at bench mark P 7 at San Jose. Subsidence near Sunnyvale from 1934 to 1954 was greater than at San Jose. Maximum subsidence from 1948 to 1954 was at San Jose and was on the order of 2.5 ft. By August 1956, subsidence at bench mark P 7 was 8.37 ft. The area of land-surface subsidence affects more than 200 sq mi, extends some 25 mi from Redwood City on the north to and beyond San Jose on the south, and has a maximum width of about 13 mi. Plots of subsidence at individual bench marks compared to fluctuation in artesian head indicate that decline in artesian head is a major cause of subsidence. The rate of subsidence is generally in accord with the rate of fluctuation of the artesian head. Subsidence virtually ceased during a period of increasing artesian head from 1937 into 1940, but was accelerated during a period of rapidly decreasing artesian head from 1944 to 1950.

DAVID T. PROPHET (Weather Engineers, Inc., 6151 Freeport Boulevard, Sacramento, California) *An Investigation of the Predictability of the Kern River Runoff to Evaluate a Precipitation-Increasing Program.* An investigation is made into the feasibility of evaluating a precipitation-increasing program designed to increase the runoff of the Kern River watershed. The problem is to determine from past data whether high correlations can be found between the Kern River runoff and other variables such as rainfall or runoff figures, or both, from other watersheds which would be unaffected by any existing similar programs. Twenty-four years of data were used in this statistical study. It is shown that multiple correlations involving more than one rainfall station or a combination of rainfall and runoff figures yield values which are satisfactory.

T. W. ROBINSON (U. S. Geological Survey, Menlo Park, California) *The Phreatophyte Problem.* The

phreatophyte problem is, in effect, a water resource problem peculiar to the arid and semi-arid regions of Western United States, that involves the consumptive waste of large quantities of ground water by phreatophytes. In Western United States there are about 80 species of phreatophytes—plants that depend upon ground water for their water requirements. These plants, which cover nearly 17 million acres in Western United States, reduce the water available to man through depletion of the ground water reservoir by an estimated 25 million ac ft a year. Use by the plants is greatest when the water table is shallow, the climate warm, and the growth dense. Consumptive waste is defined as that part of consumptive use that is without considerable benefit to man. Consumptively wasted water may be salvaged by converting consumptive waste to consumptive use. A prerequisite for evaluating ground-water salvage is data on the use of water by the phreatophytes prior to treatment. Some phreatophytes pose a flood hazard and induce sedimentation because of the reduced velocity caused by the dense growth, choking overflow channels and floodways. Dense growths immediately above storage reservoirs may act as a desilting agent and prolong the life of the reservoir, but the cost in terms of water may be excessive. Ten questions dealing with the phreatophytes, for which research should be continued and expanded, are listed.

R. Robinson Rowe, Thomas C. Royce (California Division of Highways, Sacramento, California) and Gordon L. Long (California Department of Water Resources, Sacramento, California) *Flood Frequency by Regional Synthesis.* Design of highway bridges in California has been predicated on waterways required for 30-year to 100-year floods. Determination of such floods is highly speculative because of shortness of stream-flow records. Longer records for an average stream of a hydrologically homogenous region have been synthesized by combining nondimensional peak discharges, so as to derive factors for extrapolation of frequency curves for each stream of the region. Reliability of the method, depending upon definition of homogeneity of a region, was tested by a graphical comparison. The test was devised by hypothesizing a 'perfect' 1000-year flood record and dividing it by chance distribution into twenty 50-year records. Superimposed frequency graphs of these twenty hypothetical records gave a visual measure of disparities to be expected in natural records of comparable streams. The paper, illustrated by charts, briefs the development of the graphical test, describes the application to one region in California, and shows similar results in a second region of entirely different character.

Leonard Schiff and Curtis E. Johnson (U. S. Agricultural Research Service, Bakersfield, California) *Some Methods of Alleviating Surface Clogging in Spreading Water for Recharge.* This paper discusses methods of preventing or alleviating the clogging of soil pores associated with spreading water on soil surfaces or injecting water into aquifers for recharge. Clogging appears to be reduced by vegetation, organic matter, and chemical soil treatments in that order. At the Saticoy Spreading Grounds in California, infiltration rates of 3.6 ac ft/acre day are maintained with native vegetation on a fine sandy loam even when water is spread with a suspended load up to 570 ppm. Shafts, wells, pits, trenches, and canals inject large quantities of water through a small area and hasten clogging by depositing material. At the ½-acre Peoria Pit, injection infiltration increased from an average daily volume of 3.2 to 9.5 ac ft/day when the sand filter over the aquifer was replaced with pea gravel. The filter is cleaned by suction. Injection infiltration for a $\frac{1}{10}$-acre pit at Bakersfield declined from a volume of 2 to 1.2 ac ft/day in 82 days. The pea gravel filter was not effective, and deposits on the sand aquifer beneath were removed by scraping to restore the infiltration rate. Of various filter materials being tried in infiltrometers at Bakersfield, sand ranging in size from 0.8 to 1.6 mm maintains the highest infiltration rate. Information is given on particle size distribution of both the filter and aquifer materials. Head losses due to filters and within the underlying aquifer are shown. Basins on Long Island are recharging ground water at a rate of three acre feet per acre per day. Canals on 80-ac Rohrer Island, Dayton, are recharging ground water at 107 ac ft per day. A ½-acre narrow trench infiltrated as much water as surface spreading on four acres of land at Bakersfield. Deposits are removed by scraping. High injection rates are maintained in wells along the coast at Manhattan Beach by using clear chlorinated water. Chlorine is used to prevent microbial sealing.

Zane Spiegel (New Mexico State Bureau of Mines, Santa Fe, New Mexico) *Full Development of Water Resources in New Mexico and Arizona.* Most of the principal irrigation developments in New Mexico and Arizona are located along formerly perennial streams that occupy valleys cut in unconsolidated sediments of late Tertiary age. These sediments, and the channel sediments of the rivers themselves in many places, have large permeability and tremendous amounts of ground water in transient storage under natural conditions. Extremely complex relations of recharge to ground-water reservoirs in extensive headwater and valley areas, of ground-water discharge to streams in certain areas, of movement of water from the rivers to the ground-water reservoirs in other areas, and of large evapotranspiration losses from both the streams and ground-water reservoirs occur in these areas. Although large-capacity wells and reconnaissance studies of ground-water conditions have been available in some of these areas for more than 50 years, comprehensive and realistic evaluations of the gross relations of ground-water to the total water resource picture in stream valleys have been few and far between; deliberately planned applications of the vast store of technical knowledge available to fully utilize ground-water storage along streams in New Mexico and Arizona have been nil. For example, twice as much water is consumed nonbeneficially in the Rio Grande Valley as is used beneficially. The time for an abrupt halt in large-scale development and rehabilitation of outmoded standard-type surface water systems has long passed. Water needs and our economy in these states demand

that future water conservation measures emphasize the ground-water approach for the simultaneous solution of water shortages, land drainage problems, and the elimination of the wasteful practices of existing surface-water storage, diversion, and distribution systems. Rational thinking and a realistic economic philosophy of the use and financing of water are even more important than are the applications of advanced technology to water conservation.

ROBERT G. THOMAS AND ROBERT H. BORN (California Department of Water Resources, Los Angeles, California) *Geology and Ground-Water Hydrology of San Luis Obispo County, California.* Ground-water basins in San Luis Obispo County discussed in this paper include two large inland areas (Paso Robles and Carrizo Plain Basins) and 15 small coastal basins. The Paso Robles Basin, 580,000 ac in extent, is underlain by up to 2000 ft of water-bearing sediments of Plio-Pleistocene and Recent age. Complex conditions of deposition and locally complex geologic structure of the water-bearing materials has resulted in sporadic and relatively limited use of ground water. The Carrizo Plain, 172,000 ac in extent, is an area of internal drainage underlain by more than 1000 ft of Plio-Pleistocene and Recent sediments. Low permeability of sediments, poor water quality, limited discharge and lack of convenient marketing facilities for irrigated crops together with a profitable dry-farmed economy have resulted in very limited use of ground water. The 15 coastal basins range in area from 200 to more than 16,000 ac with Arroyo Grande Basin being the most significant. The most important water-bearing sediments are alluvial materials deposited in the narrow coastal valleys during the post-Wisconsin rise in the sea level. Older water-bearing sediments are significant in some areas, however. Use of ground water during the 1953–54 season was about 26,300 ac ft in Paso Robles Basin, 600 ac ft in Carrizo Plain and 13,800 ac ft in the coastal basins for a total of 40,700 ac ft. Estimated mean seasonal water requirements under probable ultimate conditions of development will be more than ten times the 1953–54 use. In 1953, the estimated safe yield exceeded the requirements. Use of ground-water storage capacity will probably be required for regulation of imported supply as well as optimum use of local supplies. Such use of ground-water storage may require artificial recharge projects and changes in pumping pattern.

C. B. THOMPSON (Technical Division, State Engineers Office, Santa Fe, New Mexico) *Increase in Area and Density of Salt Cedar in New Mexico.* Salt Cedar (*Tamarix Pentandra*) was first reported growing in New Mexico south of Mesilla Park about 1910. In 1914 it was reported in the Lake McMillan delta area of the Pecos River. Growth in the Middle Rio Grande Valley now totals approximately 52,000 ac and in the Pecos Valley about 42,500 ac. During the last five years a sum of approximately $500,000 has been spent for eradication and control in these two river valleys by the New Mexico State Engineer and the U. S. Bureau of Reclamation. Measures used have been chemical sprays, discing, burning, lowering the water table, and others. Salt cedar growth was first confined to the lower valleys of the Pecos River and Rio Grande but is now spreading to the higher tributaries and to other stream systems such as the San Juan, Canadian, and Gila. It is believed that in the near future, if uncontrolled, it will be flourishing in every watershed in the State. Due to its excessive water consumption and the fact that it constitutes one of the major operation and maintenance problems on irrigation and flood control projects, not only in New Mexico but in the entire Southwest, it is recommended that Congressional legislation be enacted to establish a program to find a more effective means of eradication. Such a program could be similar to that used to combat halogeton in the western states during recent years.

JOHN C. THOMPSON AND EDWIN W. ELLIOTT (Irrigation Division, Albuquerque Project Office, U. S. Bureau of Reclamation, Albuquerque, New Mexico) *Conservation of Water by Channelization and Drainage of Phreatophyte Areas.* For the conservation of water and management of water salvage in the Middle Rio Grande, New Mexico, a comprehensive plan of channelization and drainage of phreatophyte areas was undertaken by the Bureau of Reclamation in cooperation with the Corps of Engineers and local interests. In one 35-mi reach of the river, in which a dense growth of phreatophytes had developed, it was estimated the annual losses averaged about 160,000 ac ft. As the result of channelization and drainage of this area, beginning in 1951, it was estimated that a total of 200,000 ac ft had been salvaged through the 1956 water year. The future annual salvage is estimated as 45,000 ac ft. In another 40-mi reach of the river the annual salvage resulting from channelization is about 40,000 ac ft. Through the construction of a network of side drains, affecting about 5000 ac, it is expected that about 8000 ac ft will be salvaged annually. One of the difficult and important jobs of maintenance is the control of vegetative growth along drains, canals, on levees, and in floodways. Areal spraying with herbicides, although effective, had to be abandoned because of apparent damage to cultivated crops, some as far as 27 mi distant. Vegetative control through mowing, burning and discing are effective, but because of rapid regrowth requires repeated treatment. A program to replace phreatophytes with grass adaptable to the area is underway.

VITO A. VANONI AND GEORGE N. NOMICOS (California Institute of Technology, Pasadena, California) *Resistance of Sediment-Laden Streams.* Observations of sediment-laden flows, such as occur in natural rivers, irrigation canals, and small flumes in the laboratory, show that the friction factors of these flows vary appreciably with the sediment transport rate. The whole problem is confused by the fact that some observations show a decrease in friction factor as the sediment load increases, while others show the opposite tendency. In order to study the problem systematically, flow experiments were made in a flume, first with a bed of loose sand, and then with the same configuration of

the bed but without any sand in motion. The results of these experiments show that in all cases a flow with a given depth and mean velocity will have a smaller friction factor when a sediment load is being carried than when the water is clear and no sediment is moved. The experiments also show, as has already been pointed out by others, that dunes forming on the bed will cause the roughness, and hence the friction factor of the stream, to reach high values. Such dunes are observed to form at low velocities and transport rates, and tend to be washed smooth by the stream at some higher velocity. This information furnishes an explanation for the variation of friction factors of streams as the sediment load and the flow rate are varied, and seems to resolve the dilemma arising from the fact that friction factors decrease with load in some instances and increase in others. Published data on this subject are discussed and explained in the light of findings of the experiments made in this study.

H. D. WILSON, JR. (Ground Water Branch, U. S. Geological Survey, Sacramento, California) *Utilization of Ground-Water Basins in Santa Barbara County, California, During 1945–52.* Comparison of water-level fluctuations during 1945–52 with the magnitude of ground-water withdrawals in several basins of Santa Barbara County demonstrates the overall utility of the basins as storage reservoirs. Ground-water withdrawals in all basins caused depletion of storage during a period, 1945–51, in which precipitation and stream flow were nearly negligible, but only the Santa Ynez River basin showed near-full replenishment in response to the above-average rainfall in the winter of 1951–52. Water levels in the remaining basins showed little or no recovery, thus indicating a state of overdevelopment for at least the period 1945–52. Groundwater inventories for the drought period show that in some basins computed storage changes are inconsistent with estimated withdrawals and recharge; quantitatively, they indicate either that sizable errors are involved in one or more items of the inventories, or that additional water was supplied during the drought period from underground sources beyond the heretofore recognized limits of the basins.

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Notes and Personalia

Notes

RECENT DEVELOPMENTS IN IGY—In connection with the schedule of participation in IGY programs [*Trans.*, **37**, 797, December, 1956] word has come from Argentina indicating participation in all disciplines instead of as shown in the chart.

In connection with the American program there is still need for more scientists and technicians on various phases of the second year of Antarctic operations which involves aurora and airglow, cosmic rays, glaciology, gravity, ionospheric physics, meteorology, and seismology. Most of the current openings relate to meteorology and glaciology. Interested candidates are invited to address inquiries to the following Antarctic Project Leaders: *Aurora and Airglow:* Norman J. Oliver, Air Force Cambridge Research Center, Laurence G. Hanscom Field, Bedford, Massachusetts; *Glaciology, Gravity, and Seismology:* Miss Diana Fisher, Glaciological Headquarters Office, USNC-IGY, Room 716, 1145-19th Street, N. W., Washington 6, D. C.; *Ionospheric Physics:* Harry G. Sellery, Central Radio Propagation Laboratory, National Bureau of Standards, Boulder, Colorado; and, *Meteorology:* Ervin A. Volbrecht, U. S. Weather Bureau, 24th and M Streets, N. W., Washington 25, D. C.

A number of international conferences have been held in the last few months relating to IGY activities, notably the Nuclear Radiation Conference in Brussels, January 22–26, 1957; Oceanographic Conference in Göteborg, Sweden, January 15–17, 1957; Western Pacific Conference in Tokyo, February 25–March 2, 1957; Africa South of the Sahara Conference at Bukavu, Belgian Congo, February 11–15, 1957; and World Data Center Conference in Brussels, March 26–28, 1957.

Work is now active in the Arctic establishing and supplying the bases during the Arctic summer. This includes the establishment of a station on the pack ice in the vicinity of 78°N 155°W, where a party of ten scientists with support of Air Force personnel will occupy the station. A second drifting station will be on an ice island in the vicinity of 82°N 110°W. It is anticipated that all Arctic stations will be in full operation by the first of July.

The various Antarctic groups are now established and are well along into the Antarctic winter. On April 2, −89° F. was noted at the Amundsen-Scott South Pole Station and unofficial reports of more recent date indicate a new world's record of −90° F. It is anticipated that the temperature at that station, 10,000 feet in altitude, may drop as low as −120° during the Antarctic winter.

The six Russian bases are now designated as follows: Mirny (main base) 66°33′S, 93°00′E, 83 persons; Pionerskaya, 69°44′S, 95°30′E, six persons; Oasis, 66°16′S, 100°44′E, three persons; Vostok, 78°30′S, 107°E, 12 persons; Sovietskaya (yet to be established as near as possible to the pole of inaccessibility); Komsomolskaya, location not given, six persons. The Soviet group reports to have photographed 15,000 sq km in the area of Mount Gauss to Bunger's Oasis and another 15,000 sq km in the Mirny-Bunger's Oasis area. Reports of other activities through 1956 and into 1957 are touched on in a brief report dated February 22, 1957.

The Japanese report that their ship *Soya* was trapped in pack ice off Prince Harold Island but broke free about March 1.

The Australians report that their annual relief of the Australian National Research Expeditions have been completed. A new station has been established at Davis, 68°34.6′S, 77°58.6′E, and will include work in meteorology, geology, and aurora.

The U. S. Coast and Geodetic Survey, which has the assignment for the American part of the program on the magnetic currents of the Earth, is operating not only at its seven permanent stations but also two temporary observatories and 15 portable stations in the United

States and Alaska. Some new instruments have been added to the regular observatories.

Arrangements are nearly complete with reference to World Days and the communication system essential to effective operation.

The British work on the upper atmosphere has been expanded to include exploration up to 90 mi using a Skylark rocket, the first of which was fired on February 13, 1957. The Skylark rocket carries a pay load of 100–120 pounds and reaches a height of 70 to 90 mi in about three minutes.

A new altitude record for single-stage rockets was set at White Sands, N. M., in April by an Aerobee-Hi rocket which went to a height of 193 miles.

Work on the U. S. satellite is continuing and the second stage rocket engine has been accepted and will soon be tested. No schedule has yet been set for the firing of the first satellite rocket. A successful test of the first and third stages of the satellite vehicle was held in April at Cape Canaveral, Florida. The test was largely an effort to determine separation techniques for the solid-fuel third stage.

TRANSLATION OF RUSSIAN SCIENTIFIC LITERATURE—An extensive project is under way by the National Science Foundation [see *Science*, **125**, no. 3248, 379–385], March 29, 1957, to translate scientific literature to English and make this available in an English printed edition. In the field of geophysics, the American Geophysical Union has recently received a grant from the National Science Foundation for the purpose of translating *Izvestiia* of the Academy of Sciences, U. S. S. R., Geophysics Series, to English and for the publication of an English edition of this. Arrangements have been entered into with the Pergamon Press, 122 East 55th Street, New York 22, New York, and Pergamon House, 4 Fitzroy Square, London W.1, England, to undertake the actual translating and printing jobs under the general guidance of an editorial board being appointed by AGU. This is for the year 1957. The project also includes a study of *Trudy* of the Institute of Geophysics of the Academy of Sciences, U. S. S. R., to see if any of the papers included in the 1957 volume should be set up as special translation projects.

There will possibly be need for assistance in translating. Candidates for this should be competent in some particular phase of geophysics as well as a student of modern Russian scientific literature. Persons interested should get into touch with the office of the American Geophysical Union or with Pergamon Press.

EXTENSION OF SEISMIC SEA WAVE WARNING SERVICE—The Coast and Geodetic Survey has announced that the seismic sea wave warning system will be extended to include forecasts for the shores of California, Oregon, and Washington. The warning system was first established in 1948 after the seismic sea wave of 1946 that killed 173 persons and did $25 million in damage in Hawaii. In 1952, and again on March 9, 1957, the seismic sea wave warning system was given a test by the seismic sea waves that occurred, and although there was some damage, no lives were lost.

CONTINUED CONTRIBUTIONS OF THE SHELL COMPANIES FOUNDATION—The Shell Companies Foundation has made grants of more than a million dollars for the third straight year to educational, charitable, religious, and public service organizations, $500,000 of which is being devoted to an educational program. Fifty-two graduate fellowships and 20 grants for fundamental research are being made to 43 colleges and universities, and 90 summer-term fellowships are being made for high school science and mathematics teachers. Further information concerning the program may be secured from the Shell Companies Foundation, 50 West 50th Street, New York 20, New York.

INDIA ADOPTS METRIC SYSTEM IN METEOROLOGY—Indian meteorologists started using the metric system in weather reports on January 1, 1957.

SOUTHWARD FLOW IN THE DEEP ATLANTIC—A massive deep current flowing south under the Gulf Stream was measured for four weeks during March and April through the cooperation of the Royal Research Ship *Discovery II* of the British National Institute of Oceanography and Research Vessel *Atlantis* of the Woods Hole Oceanographic Institution. This preliminary survey used an instrument developed by J. C. Swallow which is an electronic system similar to those used for ocean sounding. It is encased in a nine-foot piece of aluminum alloy pipe two inches in diameter, adjusted to be neutrally buoyant, so it can be sunk to a predetermined depth where its density corresponds to that of the surrounding water. It is tracked by underwater sound signals. Observations that are to be made by some 70 ships during the International Geophysical Year will be more meaningful as a result of this work. The American part of the work was under the direction of Henry Stommel and L. Valentine Worthington.

GRANTS OF THE NATIONAL SCIENCE FOUNDATION—The National Science Foundation has announced the award of 235 grants totaling over $4,000,000 in support of various aspects of science. Among the grants are ones for a randomized cloud-seeding experiment, stability of fluid flow, a study of welded tuffs of New Zealand, problem of radio astronomy, a study of chondrules in stony meteorites, a study of earthquake surface waves, isotope geology of strontium and rubidium, a study of the Beartooth Mountains, and the aggregation of ice crystals.

EXPEDITION TO THE INDIAN OCEAN—The Bingham Oceanographic Laboratory of Yale University is sending a deep-sea scientific expedition into the Indian Ocean to study the area around the Seychelles Islands. Two vessels, one a 110-ft ship and the other a 40-ft ship, will be used for collecting specimens and doing the oceanographic and hydrographic work. The expedition will be under the scientific direction of James E. Morrow, Jr.

SITE ACQUIRED FOR THE NSF RADIO ASTRONOMY OBSERVATORY—The National Science Foundation has announced the acquisition of the site for the new Radio Astronomy Observatory now in the advanced stages of planning. This will be established at Green Bank, West Virginia. The site includes about 2100 acres just north of Green Bank and west of Route 28, adjacent to lands now owned by the U. S. Forest Service. Green Bank is in Pocahontas County in southeastern West

Virginia, about 35 miles south of Elkins. This site was selected over 29 others after an extensive survey covering a large part of the country, one of the important requirements of which was the need for an absolute minimum of radio noise on wave lengths below ten meters.

FACULTY AND POSTDOCTORAL AWARDS OF THE NATIONAL SCIENCE FOUNDATION—The National Science Foundation has announced the award of 100 faculty fellowships in science for the year 1957–1958. These awards are made for the first time this year and are offered as a means of improving the teaching of science, mathematics, and engineering in American colleges and universities. The 100 designated were selected from 416 applicants. Thirty senior postdoctoral fellowships were also awarded from a list of 168 applicants.

LONG RIFT IN THE EARTH'S CRUST—Scientists of the Lamont Geological Observatory of Columbia University find evidence of a continuous rift in the Earth's crust as much as 20 miles wide and one and a half miles deep. It starts in the North Atlantic Ocean, running southerly approximately in mid-ocean around the tip of Africa into the Indian ocean. There one branch curves northward through the Arabian sea, connecting with the rift valleys that extend southerly across Africa. The other branch continues across the Indian ocean, passes between New Zealand and Antarctic, then runs toward the Macquarie Islands to Easter Island, where it turns northward toward the Gulf of California and along the coast to Alaska. It may possibly continue through the Arctic and Norwegian Seas and connect again with the starting point. A relationship of the rift to earthquake activity is under study.

DESERT RESEARCH IN EGYPT AND ISRAEL—UNESCO is giving financial aid to desert research institutes in Egypt and Israel, the total amounting to about $74,000 over a period of two years. The institutes aided are the Desert Research Institute at Mataria, near Cairo, Egypt, founded in 1950, and the Arid Zone Research Institute at Beersheba, Israel, already in operation and to be officially inaugurated in October, 1957.

MEETING OF THE ARID ZONE ADVISORY COMMITTEE—This Committee, which is undertaking the Arid Zone Research Project adopted at the Ninth Session of UNESCO in New Delhi last November, met in Paris in April. C. Warren Thornthwaite, Director of the Climatology Laboratory at Centerton, New Jersey, represented the United States. Herbert Greene of the United Kingdom was elected Chairman.

SYMPOSIUM ON INFORMATION RETRIEVAL—A Symposium on Systems for Information Retrieval was held at Western Reserve University in Cleveland, April 15–17, 1957. Nine hundred registrants took part in the sessions at which there were 40 speakers on various aspects of the problem. Further details may be secured by addressing the Center for Documentation and Communication Research of the School of Library Science, Western Reserve University, Cleveland 6, Ohio. A series of seminars will be held from July 29 to August 9, 1957, on various aspects of the problem.

NEW GRAVITY MAP OF THE NORTHWESTERN LOS ANGELES BASIN—The U. S. Geological Survey has announced the availability of a new gravity and geologic map of the Northwestern Los Angeles Basin, showing simple Bouguer gravity anomalies and the generalized geology. The scale is 1:48,000, using Bouguer anomaly intervals of one milligal. The map is available through the Geological Survey offices at a price of $0.75.

GRADUATE FELLOWSHIP AT NEW MEXICO INSTITUTE OF MINING AND TECHNOLOGY—The Sinclair Refining Company has established a graduate fellowship in geophysics at the New Mexico Institute of Mining and Technology. The fellowship initially established for one year has an annual value of $2500 with recipient to be chosen by the Institute. No services will be required of the holder of the fellowship.

SEA FRONTIERS—The third volume of the *Bulletin* of the International Oceanographic Foundation carries the new title *Sea Frontiers*. The purpose of the Foundation is 'to encourage the extension of human knowledge by scientific study and exploration of the oceans in all their aspects, including the study of game fishes, food fishes, ocean currents, the geology, chemistry and physics of the sea and the sea floor.' The *Bulletin* publishes illustrated articles on these subjects in non-technical language. Offices of the Foundation are located at the Marine Laboratory, University of Miami, Coral Gables 34, Florida.

INAUGURATION OF NEW PRESIDENT AT OHIO STATE UNIVERSITY—Novice Fawcett was recently inaugurated as President of Ohio State University. The American Geophysical Union was represented by C. Vernon Youngquist, Chief of the Division of Water of the Ohio Department of Natural Resources.

SURVEY OFF THE MEXICAN COAST—The Inter-American Tropical Tuna Commission and the Scripps Institution of Oceanography have been conducting a joint study of the possible effects on physical, chemical, and biological conditions in the ocean brought about by the presence of an isolated island. The investigation is being carried out off the west coast of central Mexico on the Scripps Research Vessel *Spencer F. Baird*.

GEOLOGICAL MEETING IN NEW ORLEANS—The Gulf Coast Association of Geological Societies will hold their forthcoming convention at the Roosevelt Hotel in New Orleans, November 6-8, 1957. Further information may be secured from Al H. Barton, 420 Shell Building, New Orleans 12, Louisiana.

ROBOT WEATHER STATION IN THE ANTARCTIC—A automatic weather station constructed by the French will be set up on the coast of Wilkes Land, several hundred miles from bases at Mawson and Davis. It will broadcast hourly weather reports over a range of about 750 miles for several months without maintenance, give wind speed and direction, barometric pressure, and temperature.

NEW ELECTROMAGNETIC SURVEY OF THE RHODESIAN SELECTION TRUST—The Rhodesian Selection Trust

in Northern Rhodesia has arranged for an electromagnetic detector survey of their holdings in Northern Rhodesia. This detector developed by Aeromagnetic Surveys of Toronto is being used in a DC 3, which was operated outside of Canada for the first time in the summer of 1956, and as a result of tests the trust has arranged with Hunting Geophysics for the new survey.

NATIONAL CLAY CONFERENCE—The Sixth National Clay Conference will be held at the University of California in Berkeley, August 19–23, 1957. Interested persons should get into touch with the Department of Conferences and Special Activities, University of California, Berkeley 4, California.

Personalia

CHARLES ALFRED ANDERSON, Chief of the Mineral Deposits Branch of the U. S. Geological Survey, has been elected to membership in the National Academy of Sciences.

DAVID ATLAS of the Air Force Cambridge Research center recently gave the annual Guenter Loeser Memorial Lecture on the subject "Progress and Prospects of Radar Meteorology."

LEDOLPH BAER is on leave from his duties with Gulf Consultants of Houston, Texas, and is studying for his doctorate at New York University.

ALLEN M. BATEMAN, Professor of Geology at Yale University, will retire in June 1957 after serving on the Yale faculty since 1915.

WERNER A. BAUM, Head, Department of Meteorology, Florida State University, has been appointed the Director of University Research, a newly established position.

JOHN W. DIXON, Chief Hydrologic Engineer for the Harza Engineering Company, has been designated one of the twelve new Associates of the Company.

WALTER M. ELSASSER of Scripps Institution of Oceanography has been elected to membership in the National Academy of Sciences.

MAURICE EWING, Director of the Lamont Geological Observatory of Columbia University and President of the American Geophysical Union, has been awarded an honorary degree of Doctor of Science by the State University of Utrecht, The Netherlands.

GAIL A. HATHAWAY, formerly Consultant to the Chief of Engineers, U. S. Army, has taken up duties with the International Bank for Reconstruction and Development.

O. W. ISRAELSEN, Professor Emeritus of Irrigation and Drainage at Utah State Agricultural College, has returned from his world tour in connection with the U. S. technical assistance missions to India, Iran, and South Africa. During his two-year sojourn, he spent almost a year as Professor of Irrigation and Drainage at the University of Roorkee in India.

JOSEPH KAPLAN, Professor of Physics, University of California at Los Angeles, and Chairman of the U. S. National Committee for the International Geophysical Year, has recently been elected to membership in the National Academy of Sciences.

SERGE A. KORFF, Professor of Physics at New York University, has been given the French Government's Order of Merit for Research and Invention.

D. B. KRIMGOLD has returned from his 13-month assignment on the FAO Technical Assistance program to the Ministry of Agriculture in Israel. During this interval and an earlier six-month tour of duty, he assisted the Soil Conservation Division and the Water Authority of Israel in setting up erosion investigations and hydrologic studies on small drainage basins, also serving as Scientific Advisor to the Israel Institute of Technology. An account of his recent work is contained in a paper by him in the Technion Yearbook for 1957 starting on page 85. He also visited various points in Yugoslavia, particularly the Karst region.

ALFRED LOEHNBERG, hydrologist from Israel, is on a UNESCO assignment to the Institute of Research in Applied Science in Mexico City for research work in ground-water hydrology.

FREDERIC T. MAVIS, Head of the Department of Civil Engineering at the Carnegie Institute of Technology, has been named Dean of the College of Engineering of the University of Maryland.

JOHN L. MERRIAM, formerly Engineer with the Soil Conservation Service at Riverside, California, has taken up duties as Senior Irrigation Engineer for the Ministry of Agriculture of Saudi Arabia.

VICTOR OPPENHEIM has opened an office in Dallas, Texas, as consultant, in cooperation with Glenn O. Briscoe, on petroleum and mineral exploration.

CARL G. PAULSEN, Chief Hydraulic Engineer of the U. S. Geological Survey, has recently retired after more than 45 years of government service. He has been succeeded by Luna B. Leopold.

LOUIS PELTIER has transferred from the Military Geology Branch of the U. S. Geological Survey and has taken up duties as Program Officer in the Office of Area Development in the Department of Commerce.

HANS PETTERSSON has retired as Director of the Gothenburg Institute of Oceanography. Einar B. Kullenberg has been named his successor.

ALFRED C. REDFIELD, Professor of Physiology at Harvard University and Associate Director of Woods Hole Oceanographic Institution at Woods Hole, Massachusetts, will retire this summer from the faculty of Harvard University.

ROGER R. REVELLE, Director of Scripps Institution of Oceanography, has recently been elected to membership in the National Academy of Sciences.

WALTER O. ROBERTS, Director of the High Altitude Observatory of the University of Colorado, has recently been appointed Professor of Astrogeophysics and Head of the University's newly created Graduate Department of Astrogeophysics.

IRA T. SANDERS, Captain and Assistant to the Director, U. S. Coast and Geodetic Survey, recently retired after more than 32 years of service with the Survey.

OSCAR JEROME BACKUS of Mojave, California, retired, died February 24, 1957, at the age of 76. He was born in Oakland, California. He took work at Lick Polytechnic School in San Francisco, but health required him to discontinue his studies. His life was devoted to the mechanical end of the work of the Eljer Company until 1914, following which he homesteaded and had been manager of rangelands near Mojave, California. He had been a member of AGU since 1947.

HAL P. BYBEE, Professor of Geology of the University of Texas, died March 31, 1957, at the age of 69. He was born at Rochester, Indiana, took his baccalaureate degree at Rochester College and a second one at Indiana University where he also took his master's and Ph.D. degree. He taught in Indiana schools from 1908 to 1911, and became an instructor in Geology at the University of Texas in 1914, where he taught until 1925. For four years he was engaged on commercial work for the Dixie Oil Company. From 1929 to 1936, he took up duties with the Board for Lease of University Lands, and since 1936 has been Consulting Geologist on University Lands and Professor of Geology. He had been a member of AGU since 1945.

ARTHUR DONALD EDMONSTON, formerly State Engineer of California, died in San Francisco, California, February 22, 1957, at the age of 70. He was born in Ferndale, California, and took his baccalaureate degree from Stanford University in 1910. He entered upon work with the State of California in 1924, following a number of years in private industry. He became Principal Hydraulic Engineer in 1927, and in 1945 he was made Assistant State Engineer, and designated as State Engineer in 1950. He retired in 1955. He was a member of AGU from 1951 to 1956.

LEON SHERMAN, member of the staff of the Los Alamos Scientific Laboratory of the University of California, died March 2, 1957 from injuries received in an automobile accident. He was born in Akron, Ohio, December 1, 1918. He took his B.A. degree from the University of California at Los Angeles in 1939, his M.A. degree from the same University in 1941, and his doctorate in 1950. During the world war he served as Aerological Officer in the Navy, following which he took up teaching duties in the Department of Meteorology, University of California at Los Angeles, in 1946, and from 1949 to 1951 he was Research Associate of the Institute of Geophysics of UCLA. From 1951 to 1955 he taught at Florida State University, leaving there as Associate Professor to take up duties at the Los Alamos Scientific Laboratory. He had been a member of AGU since 1949.

Union, Section, and Committee Activities

Thirty-Eighth Annual Meeting (1957)

Minutes, General Assembly and Section Meetings

Smoker

The Smoker was held in the Ball Room of the National Press Club, National Press Building, Fourteenth and F Streets, N. W., Washington, D. C., on the evening of Monday, April 29, 1957. Although the gathering, as usual, was entirely informal to provide a pleasant opportunity to greet old friends and meet new ones, special arrangements had been made by President Ewing for an advance showing of the third of the Bell Laboratories science films to be used on television with the release date about a month hence. This one related to cosmic rays and took about an hour to show. This still permitted the gathering of small discussion groups as in previous years.

Evening Session

The Evening Session was called to order by Past President, Leason H. Adams, at 20h 00m, Tuesday, April 30, 1957 in the Lecture Room of the National Academy of Sciences, 2101 Constitution Avenue, N. W., Washington, D. C. About 200 were in attendance. After preliminary remarks, Chairman Adams introduced President Ewing, who paid tribute to the United States Coast and Geodetic Survey which is celebrating its Sesquicentennial Anniversary this year. He mentioned a few of the highlights of the history of the Survey and then went into some of the details of his own interesting and intimate associations with the Survey during the last thirty years.

Following this, Chairman Adams called on J. Tuzo Wilson, Vice President of the International Union of Geodesy and Geophysics and Chairman of the Canadian Committee on Arrangements for the Eleventh General Assembly, who made a brief statement regarding the Eleventh General Assembly which is to be held in Toronto, September 3 to 14, 1957. He extended a cordial invitation to all members of the American Geophysical Union and their guests to attend the Assembly.

Chairman Adams then introduced Beno Gutenberg, member of the William Bowie Medal Committee, who cited Maurice Ewing as the Nineteenth Recipient in accordance with the remarks set forth on the opening pages of this issue. Chairman Adams then made the presentation, and the Recipient indicated acceptance in his response.

Chairman Adams next introduced Walter H. Munk, who made the address of the evening on the subject, Rotation of the Earth: A Geophysical Discussion. At the close of his address a social hour with refreshments was held in the Auditorium of the National Academy of Sciences.

General Assembly: Papers on Frontiers in Geophysics and Business Meeting

The General Assembly was called to order by Chairman Philip H. Abelson (Chairman of the Committee on Meetings) at 14h 00m, Wednesday, May 1, 1957, in the Auditorium of the National Academy of Sciences. About 300 were in attendance. Chairman Abelson introduced the speakers and their subjects as follows. The abstracts of the papers are to be found in the Reviews and Abstracts of this issue of the *Transactions*.

Frontiers in Geophysics

(1) Homer E. Newell, Jr.: The Scientific Uses of Artificial Earth Satellites

(2) Sverre Petterssen: Physical and Statistical Approaches to the Problem of Weather Prediction

(3) L. T. Aldrich: The Measurement and Applications of Mineral Ages

Following a brief intermission the Business Meeting was called to order by President Ewing.

The minutes of the business meeting of the 37th Annual Meeting [see *Trans.* **37**, 383–385, 1956] were approved.

Report of the General Secretary

General Secretary Sayre made a summary report outlining items covered in more detail in the reported minutes of the Executive Committee meetings. He pointed out that we are holding our own financially. Membershipwise he noted that there are still many qualified persons who are not members. The assistance of individual members was requested. He pointed out that to facilitate this a new directory of members appears in the April issue of the *Transactions*, which should be of assistance in telling who are now members. Application forms also appear in that issue. Recapitulation of changes in membership since April 25, 1956, is given as follows:

Membership as of April 25, 1956	5040	
Reactivated	6	
New Members (including 29 applications now being processed)	253	5299
Resigned	112	
Inactive	7	
Dropped	183	
Deceased	31	333
		4966
Adjustment by count of July, 1956		14
Membership as of April 18, 1957		4980

He read the names of the 31 members whose deaths had been reported in the last year and whose names

are cited in the reports of meetings of the Executive Committee and in the brief obituaries carried in the news items in the *Transactions*. Especially cited was the passing on July 29, 1956, of our greatly honored and beloved Honorary President, John A. Fleming.

Report of Standing Committees

Chairman Philip H. Abelson reported that 1076 persons had registered thus far (final figure 1132 at the close of the meeting on May 2, 1957). He stated the Annual Meeting of next spring will be held on the Monday, Tuesday, and Wednesday following the meeting of the National Academy of Sciences. The dates are probably May 5 to 7, 1958, inclusive. President Ewing remarked that he has been coming to these meetings for the past 30 years and that they have been consistently the most stimulating meetings that it has been his privilege to attend. He expressed the opinion that the 38th Annual Meeting had proved to be the best of all and thanked Chairman Abelson for his efforts in making it so.

Report of Special Committees

Resolutions—Chairman John N. Adkins presented four resolutions, all of which were unanimously adopted as follows:

(1) RESOLUTION OF THANKS FOR THE USE OF FACILITIES

WHEREAS, The District of Columbia Chapter of the American Red Cross has provided the use of its Auditorium for the Thirty-Eighth Annual Meeting of the American Geophysical Union, therefore be it

RESOLVED, That the American Geophysical Union express its great appreciation of this cooperation and instructs the General Secretary to express the thanks of the Union to the appropriate official.

(2) RESOLUTION OF THANKS FOR THE USE OF FACILITIES

WHEREAS, The National Academy of Sciences has provided the use of meeting rooms and other services for the Thirty-Eighth Annual Meeting of the American Geophysical Union, therefore be it

RESOLVED, That the American Geophysical Union express its great appreciation of this cooperation, extended over many years, and instructs the General Secretary to express the thanks of the Union to the appropriate official.

(3) RESOLUTION OF THANKS FOR THE USE OF FACILITIES

WHEREAS, The United States Public Buildings Administration has provided the use of a meeting room and other services for the Thirty-Eighth Annual Meeting of the American Geophysical Union, therefore be it

RESOLVED, That the American Geophysical Union express its great appreciation of this cooperation, extended over many years, and instructs the General Secretary to express the thanks of the Union to the appropriate official.

(4) RESOLUTION OF THANKS FOR THE USE OF FACILITIES

WHEREAS, The success of the Pacific Southwest Regional Meeting at Sacramento, California, on February 14 and 15, 1957, was due in large part to the space and facilities generously provided by the State of California, therefore be it

RESOLVED, That the thanks of the American Geophysical Union be extended to the State of California for the use of their meeting rooms and other facilities, and that the General Secretary be instructed to forward a copy of this resolution to the appropriate official of the State of California.

New and Unfinished Business

The matter of our relationships with our parent body, the National Academy of Sciences—National Research Council, was then brought up by Merle A. Tuve, who is a member of the Council of the National Academy. He pointed out that the AGU as a whole is the U. S. National Committee of the IUGG but that many of the aspects of AGU activities are on the order of scientific society activities; this leaves matters rather mixed up which in due course need to be clarified. President Ewing pointed out that this problem has been under discussion in various ways since the first meeting that he attended about 30 years ago and is of vital concern to every member of AGU. He invited word from those who had something to offer. F. N. Frenkiel noted the dissimilarity between the organizations of the International Union of Theoretical and Applied Mechanics and the International Union of Geodesy and Geophysics. Further comment is invited.

Meeting adjourned at 16h 28m.

A. NELSON SAYRE, General Secretary
WALDO E. SMITH, Executive Secretary

Appendix A—Minutes of the Annual Meeting of 1957, Section of Geodesy, American Geophysical Union

President Schmidt called the meeting to order in the Auditorium of the National Academy of Sciences at 09h 00m on April 30, 1957. The business session and all discussion of papers were deferred until all papers on the program had been presented by the authors or their representatives due to the length of the program and the importance of the papers.

The scientific session proceeded with reading of the following papers:

(1) J. E. R. ROSS: Reciprocal Crossings in Geodetic Leveling (presented by L. A. Gale)

(2) EUGENE A. TAYLOR: A New Timing Method for Second-Order Astronomic Longitude Determination

(3) W. A. HEISKANEN: The Columbus Geoid

(4) J. LAMAR WORZEL: Test of Graf Sea Gravimeter

(5) L. G. D. THOMPSON: An Improved Pendulum Apparatus for Relative Gravity Determinations

(6) S. W. HENRIKSEN, S. H. GENATT[a], M. Q. MARCHANT, and C. D. BATCHLOR: Surveying by Occultations

(7) EARL S. BELOTE: The Geodesic Line
(8) JOHN A. O'KEEFE: Geodesy and the Artificial Satellite

[a] Denotes speaker.

Discussions of the papers followed presentation of the last one.

Business Session: Announcements were made by the President. The minutes of the 1956 meeting were approved as published [*Trans.* **37**, 385, 1957]. There were no committee reports and no other business was transacted.

Approximately 110 members and guests were in attendance. The meeting adjourned at 11h 55m.

FRANK L. CULLEY, Secretary

Appendix B—Minutes of the Annual Meeting of 1957, Section of Seismology, American Geophysical Union

President Benioff called the Thirty-Eighth Annual Meeting of the Section of Seismology to order at 09h 00m on April 30, 1957 in the Auditorium, General Services Building. The minutes of the 1956 meeting were approved as published [*Trans.* **37**, 385, 1956].

L. M. Murphy reported that the Eastern Section of the Seismological Society of Ameria would welcome a joint meeting with the American Geophysical Union's Section of Seismology, but they have already made arrangement for the 1957 and 1958 meetings. The Eastern Section desires to maintain an informal atmosphere at their meetings and would want to publish their papers in their own journal. It is hoped that a joint meeting can be scheduled in the near future.

Frank Press suggested that in the future the schedule be arranged so as to avoid conflicts between the Section of Seismology and the Section of Tectonophysics.

Hugo Benioff suggested that in future meetings some of the papers given on the West Coast at the Seismological Society of America meeting might be presented again at the Section of Seismology meeting for the benefit of those who cannot attend the earlier meeting.

This concluded the business session. In addition to the scientific papers listed below that were presented at this session, a Symposium on Structure of the Sub-Oceanic Crust was held jointly with the Sections of Oceanography and Tectonophysics at 14h 00m, April 30, 1957 in the Auditorium of the National Academy of Sciences, and is reported under the Section of Tectonophysics.

(1) BENO GUTENBERG: Microseisms with Periods of About Two Seconds in Southern California
(2) LEON KNOPOFF: The Generation of Love Waves
(3) FRANK PRESS: Internal Friction in the Mantle and Rigidity of the Earth's Core
(4) GERALD R. MACCARTHY: The Virginia Earthquake of August 27, 1833
(5) OPEN DISCUSSION: The Aleutian Island and San Francisco Earthquakes of March 1957
  (a) RUTLAGE J. BRAZEE: A slide of the earthquake distribution in the Aleutians was shown and discussed. There were no concentrations in any particular area, the shocks being quite evenly distributed throughout the region. They were mostly associated with the island ridges rather than the passages between the islands. There were over 400 shocks of which the largest was of magnitude 8¼ to 8½, and there were at least 16 of magnitude 6¾ or larger.
  (b) L. M. MURPHY: The Seismic Sea Wave Warning System as operated by the Coast and Geodetic Survey is a closely woven network of nine seismograph and 17 tide stations reporting unusually large earthquakes and high water waves in the Pacific Ocean through United States military and Civil Aeronautics Authority communication facilities to a central station at the Honolulu Magnetic Observatory which appraises the data and issues warnings of possible damaging seismic sea waves to the Hawaiian Islands, other islands of the Pacific, and the west coast of the United States. The system went into full operation following the magnitude 8 earthquake of March 9. A chronological outline of this operation was given in some detail including a few of the highlights as: locating the epicenter within an hour and a half; receiving preliminary tide reports and notifying Commander-in-Chief of the Pacific (Cincpac) of possible destructive water wave within an hour and a half; receiving definite reports of unusual wave heights, initiating alert action with Cincpac and Honolulu police, and giving expected wave arrival time at Hawaii within 2½ hours; notified within 3½ hours Civil Defense in Washington, Oregon, and California of expected wave arrival along west coast; other actions were discussed until the alert was called off by Cincpac 11 hours after the earthquake occurred.
  (c) HUGO BENIOFF: The Galton low-sensitivity tidal strain seismograph showed that all of the strong shocks from the Aleutian Islands appeared at the time of maximum or minimum tidal strain for Pasadena. This might correspond to the points of maximum or minimum rate of change at the source.
  (d) BENO GUTENBERG: Before the Aleutian shocks we had had a period of unusually low seismic activity all over the world. These shocks seem to have initiated a period of normal activity.

JAMES A. PEOPLES, Secretary

Appendix C—Minutes of the Annual Meeting of 1957, Section of Meteorology, American Geophysical Union

The Thirty-Eighth Annual Meeting of the Section of Meteorology was held April 29–May 2, 1957, in the auditoria of the National Academy of Sciences, General Services Building, and the American Red Cross Building. All meetings, except the opening business session, were held jointly with the American Meteorological Society.

The business session was called to order at 09h 30m, April 29, 1957, by President H. E. Landsberg. Since no corrections were received, the Chairman declared the minutes of the Thirty-Seventh Annual Meeting of the Section of Meteorology approved as published [*Trans.* **37**, 386, 1956]. Brief reports were presented by Harry Wexler, Chairman of the Committee on the Upper Atmosphere, and by Conrad Mook, Meteorological Editor for the *Transactions*. The Chairman then appointed a Committee on Resolutions (W. H. Haggard, Chairman; H. W. Hiser; I. Dordick).

This concluded the business session, which was followed at 10h 00m by the presentation of the following scientific papers:

Monday, April 29, 1957, 09h 00m, Auditorium, National Academy of Sciences

General Session (Hugh W. Ellsaesser, Chairman)

(1) IRVING I. SCHELL: On the Nature of Tropical Storm Relationships (15 min.)
(2) ROBERT A. HOOVER: Empirical Relations between the Maximum Wind and Central Pressure of Hurricanes Entering the Coast North of Jacksonville and the Maximum Height of the Surge (10 min.)
(3) ROSS GUNN AND B. B. PHILLIPS: An Experimental Investigation of the Effect of Air Pollution on the Initiation of Rain
(4) PETER HANNA: The Research Program of Project AROWA (15 min.)
(5) S.-K. KAO: On the Oscillation of Air Particles and Its Effects on Trajectory in the Atmosphere

Monday, April 29, 1957, 14h 00m, Auditorium, National Academy of Sciences (Vaughn D. Rockney, Chairman)

Modern Developments in Radar Meteorology

(6) M. P. LANGLEBEN: Multiple-Level Radar Maps of Precipitation Patterns
(7) K. L. S. GUNN: Radar Aspects of Precipitation Physics (15 min.)
(8) MYRON G. H. LIGDA: Radar Contributions to Synoptic and Dynamic Meteorology (15 min.)
(9) HOMER HISER: Radar Detection of Severe Storms (15 min.)
(10) VAUGHN D. ROCKNEY: Observational Techniques in Radar Meteorology (15 min.)

Cloud Physics

(11) ROSCOE, R. BRAHAM, JR.: Precipitation Processes as Revealed by First Radar Echoes—Arizona 1955 (15 min.)
(12) J. DOYNE SARTOR: The Force and Electrical Field between Cloud Droplets in a Uniform Electrical Field (10 min.)
(13) B. VONNEGUT, C. B. MOORE, AND E. F. COMSTOCK: Observations of the Electrification of Cumulus Clouds (20 min.)

Monday, April 29, 1957, 14h 00m, Reading Room, National Academy of Sciences (Morton L. Barad, Chairman)

Project Prairie Grass: A Study of Atmospheric Diffusion

(14) MORTON L. BARAD: A Background History of Project Prairie Grass (20 min.)
(15) H. E. CRAMER: Organization and Objectives of MIT's Field Experiments during Project Prairie Grass (10 min.)
(16) F. A. RECORD: Diffusion Measurement Techniques Used during Project Prairie Grass (20 min)
(17) H. C. VAUGHAN: Meteorological Instrumentation Used by MIT during Project Prairie Grass (15 min.)
(18) MAURICE H. HALSTEAD AND R. L. RICHMAN: The Micrometeorological Program of Texas A and M at O'Neill, Nebr., 1956 (20 min.)
(19) ROBERT G. FLEAGLE: The Temperature Distribution just above the Prairie Surface (15 min.)
(20) PAT. J. HARNEY: Aerograph Data from an L-20 Aircraft (15 min.)
(21) VERNER E. SUOMI: Power Spectrum Analysis on Sonic Anemometer Wind and Temperature Measurements (20 min.)

Tuesday, April 30, 1957, 09h 00m, Auditorium, National Academy of Sciences (Harry Wexler, Chairman)

Meteorology: An Outlook for the Future, A Symposium

(22) GEORGE P. CRESSMAN: The Role of Numerical Analysis and Prediction
(23) JEROME NAMIAS: Weather Forecasting in Transition—A Survey and Outlook
(24) JAMES M. AUSTIN: The Local Forecast Problem
(25) THOMAS O. HAIG: Future Meteorological Instrumentation
(26) ROBERT D. FLETCHER: The Trend in Requirements for Meteorological Logistics and Personnel

Tuesday, April 30, 1957, 14h 00m, Auditorium, D. C. Chapter, American Red Cross (Thomas F. Malone, Chairman)

Numerical and Objective Prediction

(27) CARLOS R. DUNN: Incorporation of Numerical Short-Range Prognoses in Five-Day Circulation Forecasts (15 min.)
(28) PHILIP D. THOMPSON: Numerical Prediction: An Exposition and Review for the Nonspecialist (25 min.)

(29) WILLIAM E. HUBERT: Numerical Sea-Condition Forecasts (10 min.)
(30) MILES F. HARRIS: An Investigation of 1000-500-mb Thickness Changes (15 min.)
(31) R_3 G. MILLER, G. M. HOWE, AND D. G. FRIEDMAN: An Evaluation of Certain Synoptic-Climatological Aids to Weather Forecasting (15 min.)
(32) WILLIAM H. KLEIN: An Objective Method for Predicting Five-Day Mean Temperatures (15 min.)
(33) R. J. SHAFER AND W. L. SOMERVELL: Objective Forecasting for the Norfolk (Va.) Area (10 min.)

Wednesday, May 1, 1957, 09h 00m, Auditorium, D. C. Chapter, American Red Cross (Frederick G. Shuman, Chairman)

Theory of Atmospheric Motions

(34) J. K. ANGELL: Lagrangian Wind Fluctuations at 300 mb as Obtained from Transosonde Flights (20 min.)
(35) HERBERT RIEHL AND DAVE FULTZ: The General Circulation in a Dishpan Experiment with Steady Long Waves and Jet Stream (20 min.)
(36) JOSEPH SMAGORINSKY: The General Circulation Research Program of the U. S. Weather Bureau (20 min.)
(37) V. DOYLE URBAN, LOWELL P. RIGGS, AND KAZUO WATANABE: After-effects of Squall Lines and Thunderstorms (15 min.)
(38) ROBERT G. FLEAGLE: A Linear Theory of Pressure Tendency and Vertical Velocity (15 min.)
(39) ALFRED K. BLACKADAR AND KAJIT BUAJITTI: Diurnal Wind-Structure Variations in the Planetary Boundary Layer (10 min.)
(40) H. A. PANOFSKY AND A. K. BLACKADAR: On the Theory of the Formation of Turbulence by Horizontal Windshear (10 min.)
(41) R. J. LIST: The Concentration of Nuclear Debris in the Air as a Meteorological Variable (15 min.)

Wednesday, May 1, 1957, 09h 00m, Auditorium, General Services Building (Charles R. Dale, Chairman)

Instruments and Observations

(42) EDWARD P. NEY AND RAYMOND W. MAAS: The Measurement of Air Temperature under Varying Conditions of Radiation and Convection (15 min.)
(43) AYLMER H. THOMPSON AND C. R. DICKSON: A Semi-Automatic Micrometeorological Measuring System (15 min.)
(44) ROBERT E. RUSKIN: An Aerograph for Humidity-Temperature Soundings from Aircraft (15 min.)
(45) R. E. WYETT, M. G. TALCOTT, AND P. P. STARKE: Recent Developments in the Weather Bureau's Surface Observational Program (15 min.)
(46) D. W. HOLMES AND L. F. HAFER: Recent Developments in the Weather Bureau's Upper-Air and Radar Programs (15 min.)
(47) W. W. SHINNERS AND J. A. SHIRLEY: Recent Developments in Marine Instruments and Observations (15 min.)
(48) WALTER E. HOEHNE: The Use of a Constant-Volume Balloon for High-Altitude Soundings (15 min.)
(49) JOHN E. MASTERSON: The Use of Rocket-Ejected Chaff and Metalized Parachutes to Measure Winds above 100,000 Feet (10 min.)

Wednesday, May 1, 1957, 13h 30m, Lecture Room, National Academy of Sciences

Color Films of Project Prairie Grass

(50) H. E. CRAMER and P. J. HARNEY: A 30-minute color motion picture of the activities of Project Prairie Grass, described in one of the Monday afternoon sessions (30 min.)

Thursday, May 2, 1957, 09h 00m, Auditorium, National Academy of Sciences (Bernhard Haurwitz, Chairman)

The Upper Atmosphere

(51) J. ALLAN HYNEK AND FRED L. WHIPPLE: Instrumentation for the Observation of the IGY Satellites (15 min.)
(52) FRED L. WHIPPLE AND GERHARD F. SCHILLING: Upper-Atmosphere Data Expected from the IGY Satellite Tracking Program (10 min.)
(53) R. E. MCCROSKY AND GERHARD F. SCHILLING: Luminous Intensities from IGY Satellites during the Last Flight Stages (10 min.)
(54) LEITH HOLLOWAY: Correcting for Unavoidable Smoothing of Artificial Satellite Data (15 min.)
(55) SIEGFRIED J. BAUER: A Possible Troposphere-Ionosphere Relationship (15 min.)
(56) MALCOLM D. ROSS: Use of Time-Lapse Cameras at High Altitude for Observing Weather Dynamics (12 min.)
(57) B. VONNEGUT AND BERTON M. ATKINSON: Time-Lapse Motion-Picture Photography Looking down from High-Altitude Balloons (17 min.)
(58) MALCOLM D. ROSS AND M. LEE LEWIS: High-Altitude Manned Balloons for Further Meteorological Research (15 min.)
(59) WAN-CHENG CHIU: The Observed Mean Monthly Wind Fields in the Lower Stratosphere and Upper Troposphere over North America (15 min.)

Thursday, May 2, 1957, 09h 00m, Auditorium, D. C. Chapter, American Red Cross (Fred D. White, Chairman)

Meso- and Micro-Scale Phenomena

(60) NORMAN K. WAGNER: A Description of a Micrometeorological and Oceanographic Measurement Program in conjunction with Radio Propagation Tests over the Gulf of Mexico (20 min.)

(61) NICHOLAS E. MANOS: Meteorology in Air Pollution (10 min.)
(62) JAMES H. MEYER AND J. R. BAUER: Microvariations of Water Vapor in the Lower Troposphere (15 min.)
(63) NICHOLAS E. MANOS: Tornadoes Spread Disease (10 min.)
(64) WARREN SMITH: Mesoanalysis of a Tornado-Producing Situation in Texas (15 min.)
(65) GEORGE T. DELLERT, JR.: An Experiment in the Mesoanalysis of Upper-Air Data (20 min.)
(66) WALTER H. HOECKER, JR.: Life History and Measurements of Scottsbluff Tornadoes of June 1955 (15 min.)

Thursday, May 2, 1957, 14h 00m, Auditorium, National Academy of Sciences (Reinhart C. Schmidt, Chairman)

Forecasting

(67) R. A. ALLEN, J. O. ELLIS, AND J. M. SASSMAN: Some Uses of Prognostic Charts in Weather Forecasting (15 min.)
(68) FREDERICK SANDERS: Some Relationships between Vertical Velocity and Weather (15 min.)
(69) A. JAMES WAGNER: Mean Temperature from 100 to 500 mb as a Predictor of Precipitation Type (10 min.)
(70) ROBERT C. CURTIS: Large-Scale Vertical Motion, Stability, and Thunderstorm Occurrence in July 1955 (10 min.)
(71) JACK C. THOMPSON: A Generalized Analysis of Forecasting Decisions (15 min.)
(72) F. W. REICHELDERFER: Remarks on Trends in Central Weather Analysis Affecting Local Forecasting Practices (10 min.)
(73) PHILIP D. THOMPSON: Uncertainty of Initial State as a Factor in the Predictability of Large-Scale Atmospheric Flow Patterns (20 min.)
(74) G. J. FERBER, L. R. QUENNEVILLE, AND G. W. REISS: An Evaluation of a Simple Technique for Routine Fallout Determination (15 min.)
(75) HAROLD L. CRUTCHER: Cyclone Distributions Along the East Coast of Asia as Characterized by the Bivariate Normal Distribution (15 min.)

In addition to the above program, Lloyd V. Berkner, Vice President of the American Geophysical Union, gave an inspiring address on Horizons of Meteorology. The occasion was the banquet given by the American Meteorological Society in the Ballroom of the National Press Club, Wednesday evening, May 1, 1957.

WOODROW C. JACOBS, Secretary

Appendix D—Minutes of the Annual Meeting of 1957, Section of Terrestrial Magnetism and Electricity, American Geophysical Union

The Thirty-Eighth Annual Meeting of the Section of Terrestrial Magnetism and Electricity of the American Geophysical Union was held on April 30 and May 1, 1957. The first session was called to order at 14h 00m on Tuesday April 30, 1957 in the Lecture Room, National Academy of Sciences, by President Henry R. Joesting. There were approximately 44 members and guests in attendance. The minutes of the previous meeting were published [*Trans.* **37**, 388, 1956], and as no corrections have been received, the minutes were assumed correct as published.

After routine announcements the scientific program was presented as listed below:

(1) ELWOOD MAPLE: Sub-Audio-Frequency Geomagnetic Fluctuations at College, Alaska (15 minutes)
(2) JOHN F. MCCLAY AND PAUL F. FOUGERE: Preparation of Mutually Consistent Magnetic Charts (15 minutes)
(3) T. OBAYASHI AND J. A. JACOBS: Sudden Commencements of Magnetic Storms and Atmospheric Dynamo-Action (15 minutes)
(4) EDWIN J. CHERNOSKY: Magnetic Disturbance: A Principal or a Secondary Solar Geomagnetic Effect (15 minutes)
(5) S. F. SINGER: Further Developments in the Magnetohydrodynamic Theory of Magnetic Storms (15 minutes)
(6) SERGIO G. FERRAES: A Differential Equation for the Oscillation of a Magnet in the Geomagnetic Horizontal Field (5 minutes)
(7) E. H. VESTINE: The Seasonal Variability in E-Region Winds Responsible for the Solar Daily Magnetic Variation (20 minutes)

All papers are presented by the first-named author except paper (2). The session was adjourned at 16h 30m.

The second session was called to order by President Henry R. Joesting at 09h 00m on May 1 in the Reading Room of the National Academy of Sciences. The following papers were presented:

(8) ALFRED ZMUDA AND JOHN F. MCCLAY: Preliminary Results of Extrapolation of Geomagnetic Field Components to the Boundary of the Earth's Core (10 minutes)
(9) ROLAND G. HENDERSON: Downward Continuation of Anomalies in Magnetic and Gravity Fields (20 minutes)
(10) ALLAN COX: Remanent Magnetization of an Eocene Formation from Oregon (15 minutes)
(11) J. R. BALSLEY AND A. F. BUDDINGTON: Remanent Magnetism of the Russel Belt of Gneisses, Northwest Adirondack Mountains, New York (15 minutes)
(12) C. Y. JOHNSON, J. C. HOLMES, AND E. B. MEADOWS: Ion Composition of the Ionosphere at Fort Churchill, Canada, by Rocket-Borne Spectrometers (15 minutes)
(13) J. P. HEPPNER, J. D. STOLARIK, AND L. H. MEREDITH: Rocket Measurements at WSPG,

New Mexico, July 5, 1956: Part A, Altitude Distribution of Nightglow Emissions; Part B, The Magnetic Field to 163 km (20 minutes)

Approximately 62 members and guests were present for this second session. During both of the scientific sessions there was active informal discussion from the floor following the presentation of each paper. The meeting was adjourned at 16h 20m.

R. E. GEBHARDT, Secretary

Appendix E—Minutes of the Annual Meeting of 1957, Section of Oceanography, American Geophysical Union

The meeting was called to order at 09h 15m, April 29, 1957, in the Auditorium, D. C. Chapter, American Red Cross, by President Roger Revelle. There were approximately 45 members of the Section in attendance.

Since no corrections had been received, or were made from the floor, the minutes of the 1956 meeting were declared approved as published [*Trans.* **37**, 389, 1956].

President Revelle announced that in the near future he would appoint members to the following committees:

(a) Committee on Interaction of the Sea and Atmosphere
(b) Nominating Committee
(c) Committee on Report on American Oceanography for the September 1957 Meetings of the IUGG at Toronto

Announcements were made concerning the Annual Smoker, the IUGG meetings in September, 1957, in Toronto, and additions to the program for the present meeting.

The Business Meeting was then adjourned and was followed by the scientific sessions. In addition to the program listed below, a Symposium on Structure of the Sub-Oceanic Crust was held jointly with the Sections of Tectonophysics and Seismology at 14h 00m, April 30, 1957, in the Auditorium of the National Academy of Sciences. This joint session was organized by Harry Hess, and is reported under the Section of Tectonophysics. A brief preliminary report on the seismic sea wave of March 9, 1957 was given by Bernard Zetler of the U. S. Coast and Geodetic Survey. J. E. Dinger of the Naval Research Laboratory presented some slides showing wave spectra in the band of 1 to 100 cycles per kilosecond, as complimentary data to the paper given by Walter Munk and Frank Snodgrass. These two brief presentations were not listed on the regular program, which follows:

(1) CHARLES C. BATES: Recruitment and Salary Problems in the Oceanographic Profession as of Late 1956
(2) FRANK CHEW: The Hydrography of the Florida Gulf Coast Water
(3) R. J. URICK, L. C. PHARO, AND E. SKUDRZYK: A New Method for Measuring the Thermal Microstructure of the Sea
(4) ALLEN H. SCHOOLEY: Short-Fetch Water Wave Slope Probability Distributions
(5) DONALD W. HOOD, KILHO PARK, AND J. B. SMITH: Bicarbonate Ion as a Source of Carbon for Marine Plants, and Its Oceanographic Significance

Monday, April 29, 1957, 14h 00m, Lecture Room, National Academy of Sciences

(6) C. L. BRETSCHNEIDER: Joint Distribution of Wave Heights and Lengths
(7) FRANK SNODGRASS AND WALTER MUNK: Off-Shore Recording of Ocean Waves in the Band of 1 to 100 Cycles per Kilosecond
(8) WALTER MUNK AND FRANK SNODGRASS: Some Recent Results in the Study of Ocean Waves in the Band of 1 to 100 Cycles per Kilosecond
(9) WILBUR MARKS: The Directional Spectrum of a Wind-Generated Sea, Part I, Method of Observation and Data Reduction
(10) WILLARD J. PIERSON, JR.: The Directional Spectrum of a Wind-Generated Sea, Part II, Analysis of Data and Results

Tuesday, April 30, 1957, 09h 00m, Lecture Room, National Academy of Sciences

(11) ARTHUR R. MILLER: Report on the Effect of Winds on Coastal Water Levels of New England
(12) B. J. GILETTI AND F. BAZAN: Near-Surface Ocean Circulation from Tritium Measurements
(13) WALLACE S. BROECKER: Variations in the C^{14}/C^{12} Ratio of Atlantic Ocean Surface Water
(14) WALLACE S. BROECKER, ROBERT D. GERARD, AND BRUCE C. HEEZEN: Deep Water Circulation in the Atlantic Ocean
(15) D. W. PRITCHARD: On the Question of Nontidal Drift in Estuaries

Wednesday, May 1, 1957, 09h 00m, Lecture Room, National Academy of Sciences

(16) IRVING I. SCHELL: On the Role of the Oceans in the Climates of the Pleistocene
(17) GEORGE H. SUTTON, HANS BERCKHEMER, AND JOHN E. NAFE: Physical Aspects of Deep-Sea Sediments
(18) JOHN E. NAFE AND CHARLES L. DRAKE: A Comparison of Deep and Shallow Water Marine Sediments
(19) WILFORD F. WEEKS AND OWEN S. LEE: Observations on the Growth of Sea Ice at Hopedale, Labrador
(20) KARL K. TUREKIAN: The Significance of Variations in the Strontium Content of Deep-Sea Cores

DONALD W. PRITCHARD, Secretary

Appendix F—Minutes of the Annual Meeting of 1957, Section of Volcanology, Geochemistry, and Petrology

President Schairer called the meeting to order at 09h 00m, April 29, 1957. No corrections having been received, the minutes of the Annual Meeting of 1956 were approved as published [*Trans.*, **37**, 390, 1956]. President Schairer discussed briefly the concern of our Section for broadening the scope of activities of the International Association of Volcanology. The first technical session began at 09h 10m. The program sponsored by our Section was as follows.

Monday, April 29, 1957, 09h 00m, Auditorium, General Services Building

(1) J. V. SMITH[a] AND T. G. SAHAMA: Phase and Structural Relations in the Nepheline-Kalsilite System
(2) GEORGE R. RAPP, JR.: The Synthesis of Zoisite in the Pressure Range 1000–5000 bars
(3) TARO TAKAHASHI: Supergene Alteration of Zinc-Lead Deposits
(4) F. DONALD ECKELMANN[a], J. S. BROWN, AND J. LAURENCE KULP: Relationships between Lead Isotope Composition, Pattern of Mineralization, and Composition of Ore Solutions in the Bonne Terre Mine, Southeastern Missouri
(5) ALLEN M. ALPER AND ARIE POLDERVAART[a]: Zircons from the Animas Stock and Associated Rocks, New Mexico
(6) RAE L. HARRIS[a] AND ARIE POLDERVAART: Zircons of Archean Rocks from the Beartooth Mountains, Montana and Wyoming
(7) LEONARD H. LARSEN[a] AND ARIE POLDERVAART: Zircons of the Bald Rock Batholith, California
(8) HARRISON BROWN[a] AND CHARLES R. MCKINNEY: The Existence of Specific Groups of Chrondritic Meteorites
(9) H. HAMAGUCHI, G. W. REED[a], AND ANTHONY TURKEVICH: The Uranium and Barium Contents of Meteorites
(10) GEORGE K. BATE[a] AND J. R. HUIZENGA: Determination of Thorium in Meteorites by Neutron Activation
(11) ELIZABETH RONA: A Method to Determine the Isotopic Ratio of Thorium^{232} to Thorium^{230} in Minerals

Monday, April 29, 1957, 14h 00m, Auditorium, General Services Building

(12) CLARENCE S. ROSS: Welded Tuffs from a Deep Well in Southeastern Georgia; Volcanism of Probable Early Paleozoic in the Georgia-Florida Region
(13) MATT WALTON: On the Logic of Geology
(14) O. F. TUTTLE[a] AND C. P. THORNTON: The Differentiation Index as a Tool for Classifying the Igneous Rocks
(15) F. CHAYES: The δ_c Spacing in Intermediate Plagioclase
(16) ARTHUR H. BROWNLOW: The Oxygen Isotope Thermometer—A Critical Review
(17) ROBERT F. FUDALI: On the Origin of Pseudoleucite
(18) JOHN A. WOOD, JR.: The Solubility of Quartz in Water at High Temperatures
(19) P. J. WYLLIE[a] AND O. F. TUTTLE: The Effect of Volatile Materials on the Melting Temperatures of Silicates

Tuesday, April 30, 1957, 14h 00m, Auditorium, General Services Building

(20) H. R. BRANNON, JR., A. C. DAUGHTRY, D. PERRY, W. W. WHITAKER, AND M. WILLIAMS[a]: Radiocarbon Evidence on the Dilution of Atmospheric and Oceanic Carbon by Carbon from Fossil Fuels
(21) R. M. FARQUHAR[a] AND D. R. RUSSELL: Anomalous Leads from the Upper Great Lakes Region of Ontario
(22) ROYAL R. MARSHALL: Common Leads and the Continuous Development of the Crust
(23) PAUL E. DAMON[a] AND J. LAURENCE KULP: Alpha-Helium Ages of Pegmatite Zircons
(24) G. R. TILTON[a], G. L. DAVIS, G. W. WETHERILL, AND L. T. ALDRICH: Isotopic Ages of Zircon from Granites and Pegmatites
(25) OLAVI KOUVO[a] AND PAUL W. GAST: Comparative Radioactive Ages from Some Finnish Granites
(26) G. W. WETHERILL[a], G. L. DAVIS, AND L. T. ALDRICH: Age Measurements on Rocks North of Lake Huron
(27) P. M. HURLEY[a], W. H. PINSON, H. W. FAIRBAIRN, AND R. F. CORMIER: Comparison of A^{40}/K^{40} and Sr^{87}/Rb^{87} Ages on Biotite
(28) H. BAADSGAARD[a], A. O. C. NIER, AND S. S. GOLDICH: Investigations in A^{40}/K^{40} Dating
(29) S. S. GOLDICH[a], A. O. C. NIER, AND H. BAADSGAARD: $A^{40}K^{40}$ Dating of Rocks of the Lake Superior Region

[a] Denotes speaker.

This program is nearly double that of last year. Because of the inexperience of this year's officers the schedule was perhaps too strenuous to permit the amount of discussion desired. The larger program did allow the formation of somewhat more homogeneous sessions which reduce the shuffle between papers to a minimum. In future years we shall try to avoid conflicts with the Sections of Seismology and Tectonophysics.

L. THOMAS ALDRICH, Secretary

Appendix G—Minutes of the Annual Meeting of 1957, Section of Hydrology, American Geophysical Union

President Ray K. Linsley called the Business Meeting to order at 09h 15m, April 29, 1957, in the Lecture Room of the National Academy of Sciences. The President announced the names of the Section officers, the appointments made to the Executive Committee, and the Chairmen of the Research Committees of the Section. The number and titles of the Research Committees were changed this triennium to conform with the organization of the International Association of Hydrology (IAH). The appointment of new rotational members of the Research Committees will be made as of July 1, 1957. An invitation was extended for interested members to volunteer for the committee work and for suggestions concerning desirable activities to be undertaken by the committees.

The announcement was made that Walter B. Langbein has resigned as one of the Hydrology members of the Editorial and Publication Committee of the Union. The President expressed the sincere appreciation of the Section for the outstanding contributions Langbein has made during the past 12 years in helping to attain the present high editorial quality of the *Transactions*. President Linsley announced that Thomas Maddock, Jr., has accepted appointment to the Editorial Committee.

The President announced that, upon recommendation of the Hydrology Committee on Awards, the Executive Committee selected the paper "An Evaluation of Ground-Water Tracers" by W. J. Kaufman and G. T. Orlob (June 1956) as the best Hydrology paper to appear in the 1956 AGU *Transactions* and that this paper is to receive the Horton Award for that year. A Certificate of Award will be prepared and forwarded to the authors at an early date.

Secretary Ralph N. Wilson reported on activities of the Section in obtaining U. S. Hydrology papers for presentation at the Eleventh General Assembly of IUGG in Toronto, September 1957. Abstracts of 28 papers have been forwarded to Professor Tison, General Secretary of IAH, for consideration in connection with the Assembly. It is expected that copies of the complete papers can be forwarded to IAH early in June. Members of the Section were urged, in view of the proximity of Toronto, to take full advantage of the opportunity to attend the meeting of the General Assembly.

The Business Meeting then adjourned and was followed immediately by the Scientific Sessions which included two general sessions and two sessions of a Symposium on Radioactivity in Natural Waters. The first session, under the Chairmanship of President Linsley, began at 09h 25m, and was presented as follows, with 75 members and guests present:

(1) WYNDHAM J. ROBERTS: Suppressing Evaporation from Water Surfaces

(2) Discussion of Roberts' paper, as prepared by G. Earl Harbeck, was presented by E. L. Hendricks.

(3) W. D. POTTER: Relations between Low and High Frequency Peak Rates of Runoff

(4) H. C. S. THOM: A Time-Interval Distribution for Excessive Rainfall

(5) PAUL BOCK[a] AND JOHN C. GEYER: The Determination of Quantity of Storm-Water Flow on Small Urban Areas

President Linsley introduced Alfred J. Cooper, Chairman of the Research Committee on Surface Water, and stated that Copper would preside over the opening session on the Symposium on Radioactivity in Natural Waters. The session began at 14h 00m, April 29, 1957 in the Auditorium, District of Columbia Chapter, American Red Cross. Cooper acknowledged the help and assistance of a number of individuals who either furnished information or prepared papers for the Symposium. The Chairman presented a brief general discussion concerning the use of radioactive elements in the hydrologic field. The following program was presented with 71 guests and members in attendance during the course of the session.

(6) CONRAD P. STRAUB, F. J. LUDZACK, G. R. HAGEE, AND A. S. GOLDIN: Time-of-Flow Studies, Lima, Ohio (presented by Lloyd R. Setter)

(7) E. S. SIMPSON[a], W. A. BEETEM, AND F. H. RUGGLES: Radiotracer Experiments in Mohawk River, New York, to Study Sewage Path and Dilution

(8) FRANK L. PARKER: Tracers in Hydrologic Studies

(9) JOHN C. GEYER AND GEORGE T. BRYANT[a]: The Travel Time in Radioactive Wastes in Natural Waters

The second session of the Symposium, under the chairmanship of Joseph A. Lieberman, was called to order at 09h 15m, April 30, 1957, in the Auditorium, District of Columbia Chapter, American Red Cross.

(10) LLOYD R. SETTER[a] AND CONRAD P. STRAUB: The Distribution of Radioactivity from Rain

(11) F. B. BARKER[a] AND R. C. SCOTT: Uranium and Radium in Ground Waters of the Llano Estacado, Texas and New Mexico

(12) J. V. JORDAN[a], G. C. LEWIS, AND M. A. FOSBERG: Tracing Moisture Movement in "Slick-Spot" Soils with Radiosulfur

(13) H. H. HESS[a] AND W. R. THURSTON: Disposal of Radioactive Waste on Land

The last general session was called to order April 30, 1957, at 14h 00m, by Chairman E. L. Hendricks in the Reading Room, National Academy of Sciences. The session was well attended with 88 guests and members present.

(14) RAY L. LINSLEY: Correlation of Rainfall Intensity and Topography in Northern California

(15) H. G. WILM: Water-Yield Improvement in Arizona

(16) WALTER H. WISCHMEIER AND DWIGHT D. SMITH[a]: Kinetic Energy of Rainfall and Its Relationship to Erosion Losses

(17) B. J. HOLLINGSWORTH AND H. I. MEYER[a]: Two-Dimensional Gravity Drainage Profiles

(18) K. G. REINHART: Calibration of Five Small Forested Watersheds
(19) SAM SHULITS[a] AND GORDON D. BENNETT: Eddy Viscosities in Open Channels
(20) W. A. WHITE[a] AND GEORGE B. MAXEY: A Possible Mechanism for the Concentration of Brines

Following the scheduled program, Philip M. Smith, recently returned from the Antarctic, gave a very interesting, illustrated discussion on Antarctic crevasses, their types, and relationships to oversnow transport.

The meeting adjourned at 17h 00m.

RALPH N. WILSON, Secretary

Appendix H—Minutes of the Annual Meeting of 1957, Section of Tectonophysics, American Geophysical Union

President Hess called the business meeting to order at 09h 10m on April 30, 1957 in the Reading Room, National Academy of Sciences Building. The minutes of the 1956 meeting were approved as published [*Trans.*, **37**, 392, 1956]. There being no old or new business, the scientific session began immediately. President Hess and Vice President Hurley presided. The following papers were presented:

(1) DARRELL S. HUGHES[a] AND ROBERT G. MCQUEEN: Density of Basic Rocks at Very High Pressures
(2) BENO GUTENBERG: Discrepancies between Thickness of the Crust Calculated from Seismic and from Gravity Data
(3) GEORGE A. THOMPSON: Gravity Measurements between Hazen and Austin, Nevada
(4) EDGAR W. SPENCER: Fracture Patterns in the Beartooth Mountains, Montana and Wyoming
(5) H. S. HEAPS: Dependence of Internal Stress and Surface Strain upon Irregularities in an Elastic Solid
(6) W. S. JARDETZKY: On the possibility of an Aperiodic Pole Shift
(7) ANATOL J. SHNEIDEROV: The Hearth Hypothesis of the Constitution of the Earth

[a] Denotes speaker.

The session closed at 12h 15m.

The second scientific session, conducted jointly with the Sections of Oceanography and Seismology, was a Symposium on Structure of the Sub-Oceanic Crust. President Hess presided and called this session to order at 14h 02m on April 30, 1957 in the Auditorium of the National Academy of Sciences. The following papers were presented:

(8) B. C. HEEZEN: Deep-Sea Physiographic Provinces and Structural Trends
(9) H. W. MENARD[a] AND R. L. FISHER: Clipperton Fracture Zone in the Northeastern Equatorial Pacific
(10) J. B. HERSEY[a], E. T. BUNCE, R. F. WYRICK, AND F. T. DIETZ: Seismic Study of the Ocean Floor Southeast of the Blake Plateau
(11) JOHN EWING[a], J. F. HENNION, AND C. B. OFFICER: Geophysical Investigations in the Eastern Caribbean
(12) MAURICE EWING: Recent Geophysical Investigations of Oceanic Crust
(13) FRANK PRESS: Crustal Exploration using Phase Velocity of Rayleigh Waves
(14) HUGO BENIOFF: Tectonics of Pacific Continental Margins

[a] Denotes speaker.

The session adjourned at 16h 55m.

B. F. HOWELL, JR., Secretary

Russian Translation Project

With the support of a grant from the National Science Foundation, the American Geophysical Union is undertaking the translation and publication of an English edition of *Izvestiia*, Academy of Sciences, USSR, (Geophysics Series) with the aid of Pergamon Press (122 East 55th Street, New York 22, New York, and Pergamon House, No. 4. Fitzroy Square, London, W.1, England) and is to make a study of *Trudy*, Academy of Sciences, USSR (Geophysics Series) to see what parts, if any, should be set up as special translation projects. The Pergamon Press will handle sales and subscriptions, and persons interested in acquiring these should apply directly to Pergamon Press. The translations will start with the first issue of 1957 and are scheduled to include all of the numbers published in 1957.

In connection with this work, additional translators are needed on a part-time basis. Persons having a thorough knowledge of Russian and some phase of the broad field of geophysics who are interested in this should write either to Pergamon Press or to the American Geophysical Union. Should you write to the former, please send a copy of your letter to the office of AGU at 1515 Massachusetts Avenue, N.W., Washington 5, D. C.

Plans for the Reprinting of Out-of-Print *Transactions*

Over the years the stock of back numbers of the *Transactions* has been exhausted in large part and many numbers are out of print. The demand for these is continuing and, recognizing this, the American Geophysical Union has made arrangements with the Johnson Reprint Corporation, 111 Fifth Avenue, New York 3, New York, for the reprinting of out-of-print numbers. Also, the stock of back numbers prior to 1954 has been turned over to Walter J. Johnson, Inc., of the same address, for sale. After July 1, 1957, it is anticipated that the remaining stock for 1954 will likewise be turned over. Thus back numbers, more than

three years old, will no longer be available through the AGU but will need to be secured through the Johnson Reprint Corporation.

It is the plan of the Johnson Reprint Corporation to reprint the 12 earliest volumes first, following which plans for the publication of subsequent volumes will develop as demand indicates.

ELEVENTH GENERAL ASSEMBLY OF IUGG TO BE HELD IN TORONTO, CANADA, SEPTEMBER 3–14, 1957—This is the last call for those who desire to attend this meeting to send word promptly to the office of AGU in order that they may be duly registered and go with proper accreditation. The Canadian Organizing Committee has indicated that it cannot be responsible for accommodation of those who do not register promptly. All seven International Associations have arranged extensive scientific programs.

MEETINGS OF THE GEOPHYSICAL SOCIETY OF HAWAII—Eighty members and guests attended the meeting of the Society held in Honolulu, November 29, 1956. A brief résumé of the activities for the last year was given by Chairman Joel Cox, noting the dedication of Mauna Loa Observatory, the establishment of the Geophysical Institute at the University of Hawaii, and the hydrologic study of the Pearl Harbor area. H. Dean Parry was installed as Chairman during the meeting. Following this there was a panel discussion of the status and plans for geophysical research at the University of Hawaii.

On December 31, the Society held a meeting which was addressed by Harry Wexler, Director of Meteorological Research of the Weather Bureau and Vice Chairman of the Antarctic Committee of the U. S. National Committee for the International Geophysical Year. He was en route to the Antarctic.

On January 31, Hans Pettersson addressed the Society on the geochronology of the ocean floor.

On March 26, Colin S. Ramage, former Director of the Royal Observatory in Hong Kong, currently with the Hawaii Institute of Geophysics, spoke on typhoons.

ACTIVITES OF PACIFIC SOUTHWEST REGION, AGU—The Pacific Southwest Regional Meeting was held at Sacramento, California on February 14–15, 1957. There were 209 people registered for the meeting, which consisted of four sessions on a wide range of subjects in the field of hydrology and one session devoted to a symposium on the subject of phreatophytes. Twenty-eight papers were presented at these sessions. On the morning of February 15 about 25 went on field trips to Folsom and Monticello Dams, which are near Sacramento. The next meeting of the Pacific Southwest Region is to be held in Pasadena early in 1958. Vito A. Vanoni was appointed General Chairman of this meeting.

Special Announcements

TRANSLATION OF RUSSIAN SCIENTIFIC LITERATURE—As indicated in the second item under Notes, a project is now under way for the translation of certain Russian geophysical literature. There is possible need for some further assistance in translating. Persons with a knowledge of some phase of geophysics, who are also thoroughly acquainted with the Russian language and modern-day Russian scientific terminology and can devote a few hours a week to such endeavor, are invited to send applications to the office of AGU or to Pergamon Press as indicated in the news note.

PACIFIC NORTHWEST REGIONAL MEETING—Plans are developing for a meeting to be held in Pullman, Washington, in October, 1957. Interested persons should get into touch with Norbert Leupold (P. O. Box 5082, Portland 13, Oregon), Chairman of the Regional Committee, or Franklin I. Badgley (Department of Meteorology, University of Washington, Seattle 5, Washington), Secretary of the Committee.

PLANS OF THE NORTH CENTRAL REGIONAL GROUP—No late word has been received of the plans that have been developing in the Middle West, only that there is a tentative plan to hold a meeting in St. Louis or Indianapolis, the latter in connection with the meeting of the American Association for the Advancement of Science in December. Interested persons should get in touch with Edward M. Brooks (Saint Louis University, Saint Louis, Missouri), Chairman of the North Central Regional Committee; or Russell G. Mann (U. S. Weather Bureau River Forecast Center, Saint Louis, Missouri), Secretary of the Regional Committee; or with William C. Krumbein (Department of Geology, Northwestern University, Evanston, Illinois), one of AGU's two members on the Council of the AAAS.

PACIFIC SOUTHWEST REGIONAL MEETING—Plans are developing for a Pacific Southwest Regional meeting to be held in Pasadena, California, in January or February, 1958. Interested persons should get into touch with Vito A. Vanoni (California Institute of Technology, Pasadena 4, California), Chairman of the Committee.

THIRTY-NINTH ANNUAL MEETING—The Thirty-Ninth Annual Meeting of AGU will be held in Washton, D. C. in the week following the meeting of the National Academy of Sciences, probably May 5, 6, and 7, 1958. It is just possible, however, that the National Academy meeting will be held a week earlier than is now anticipated, in which case our dates will be April 28, 29, and 30. Watch these Special Announcements for further word.

Transactions
American Geophysical Union

VOLUME 38 AUGUST 1957 NUMBER 4

Greetings to the Eleventh General Assembly of IUGG

To the International Union of Geodesy and Geophysics, to the Canadian National Committee, and to the Canadian Committee on Arrangements, we extend congratulations, and to the many participants our special salutation. This number of the *Transactions* issued just prior to the opening of the Eleventh General Assembly in Toronto, September 3–14, 1957, is especially oriented to the IUGG meeting. It carries many papers originating in or relating to other lands and includes the symposium relating to geochronology that will be presented at the General Assembly.

Salute to the International Geophysical Year

The International Geophysical Year was officially inaugurated as of July 1, 1957, to continue until December 31, 1958. Timed to include the period of sunspot maximum, the International Geophysical Year follows the Second International Polar Year (1932–1933) by 25 years and the First International Polar Year (1882–1883) by 75 years.

The First International Polar Year gave the first synoptic charting of the Earth's magnetic field and resulted in the establishment of a world network of magnetic stations that operates up to the present time. The Second International Polar Year learned much about the ionosphere and the conditions that result in radio blackout and resulted in the establishment of a network of meteorological stations over the north polar region which continues to function and to exchange data freely.

The concept, initiation, and execution of the International Geophysical Year stem largely from those associated with the International Union of Geodesy and Geophysics, of which the American Geophysical Union is the U. S. National Committee. The IUGG in association with five other international unions and the World Meteorological Organization is represented on a special committee of the International Council of Scientific Unions designated to plan and organize the International Geophysical Year.

The popular press and radio have carried a great many stories in recent days concerning IGY activity, and as of July 1, 1957, the U. S. National Committee for IGY initiated a *Bulletin* which will carry authentic news of the work and developments. This *Bulletin* is circulated among the active workers in the International Geophysical Year activities and is included in the *Transactions* as a source of authoritative information for our many readers and for the permanent record.

Some Preparations for the International Geophysical Year Earth Satellite Program

HOMER E. NEWELL, JR.

Abstract—If all goes as planned, a number of small artificial satellites of the Earth will be launched during the International Geophysical Year. The IGY satellites will be launched by means of a finless three-staged rocket weighing about 11 tons. The satellites will be small, weighing on the order of 21.5 pounds. To make the utmost use of this small weight, the instrumentation must be miniaturized as much as possible, using such things as transistors and ferrite cores, and the most efficient power-supply systems obtainable. Nevertheless, there is a considerable list of worthwhile experiments that might be done in such a small satellite, including observations of solar radiation, cosmic rays, the Earth's magnetic field, the ratio of radiation influx to the atmosphere to the radiation efflux, micrometeors and dust in space, the cloud cover over the Earth, auroral particles, the density of the upper atmosphere, and geodetic parameters. The first four experiments have already been selected by the Technical Panel for the Earth Satellite Program to be attempted during the IGY. Since the last two listed require only careful observation of the satellite's motion, they will certainly be done also. The initial IGY satellites will open a new frontier of science, of engineering, and of Man's achievement. The future possibilities of research from such space vehicles are exciting to contemplate, particularly in the light of possible increases in total payload weight, and increased flexibility in the choice of orbital inclinations and altitudes.

Background—It is now a year and a half since the White House announcement that the United States would undertake the launching of an artificial satellite as a part of the research program for the International Geophysical Year. This program was generated by the U. S. National Committee (USNC) for IGY as an extension to the vertical sounding rocket program, to provide a means for making observations above the atmosphere over extended periods of time. The Department of Defense (DOD) was asked to assume responsibility for the launching of the satellite, and for logistic support of the project. DOD agreed to take on this job, and for the purpose set up Project Vanguard under the management of the Chief of Naval Research, who assigned technical responsibility to the Naval Research Laboratory (NRL). To manage and direct the scientific research in the IGY satellite program, the USNC created a Technical Panel on the Earth Satellite Program (TPESP). In the past year and a half both the TPESP and the DOD have made considerable progress, although the major hurdles are still ahead. It is the purpose of this paper to review the progress to date.

The TPESP has selected a group of experiments to be performed in the IGY satellite program. These may be separated into two classes: (a) those experiments which depend only on radio or optical tracking of the satellite, and (b) those which require active sensing elements in the orbiting vehicle plus some means for radioing the information they obtain back to the ground. In the first category are geodetic and air-density measurements. In the second category are studies of solar radiation, meteors and their effect upon the satellite, cosmic rays, Earth's magnetic field, and meteorology.

Geodetic measurements—A careful determination of the satellite orbit will be derived from radio and optical tracking information. From gravitational perturbations on the orbit, such as rate of regression of the nodes, and advance of perigee, particularly during the early part of the satellite's life when air resistance has its least effect, it is expected to determine the Earth's equatorial radius and the Earth's oblateness more precisely than they are now known. It is also expected that separate geodetic nets now in existence can be linked more accurately than hitherto.

Air densities—The air drag on the orbiting satellite will be proportional to the air density. This drag will also perturb the orbit, causing changes in the semimajor axis of the orbit, or equivalently the period of revolution, and in other orbital parameters. From these perturbations it is planned to deduce the atmospheric density at orbital altitudes, particularly in the neighborhood of perigee.

Ionospheric studies—The ionization in the ionosphere will have some effect upon the radio-

tracking signals, and it may be possible to make some deductions about the ionosphere from observation of these effects.

The studies outlined above use tracking information as the basic data. They do not require sensing elements in the satellite and radio transmission of the data obtained by those sensing elements. The ionospheric studies as now being thought of do require a radio signal to be transmitted from the satellite, but for this the tracking signal alone is sufficient. On the other hand, the geodetic and air-density studies could be made from optical observations alone. As a matter of fact, the more precise geodetic and air-density data are expected to come from the optical observations.

The remaining experiments selected by the TPESP for performance in IGY satellites require active detectors in the satellite vehicle and radio telemetering to obtain the information from them. They may be divided into four groups.

Group I: Lyman alpha solar radiation and environmental measurements—The Lyman alpha experiment is intended to determine the fluctuations in the intensity of solar Lyman alpha radiation from orbit to orbit. The detector to be used will be an ionization chamber sensitive to the wavelength band from 1100 to 1300 A, in which it is known that Lyman alpha comprises more than 95 pct of the solar output. The output of the ionization chamber will be amplified with an electrometer circuit. The amplified current will control the flux level in a magnetic core which will retain the flux corresponding to the maximum Lyman alpha signal. This memory core will be the frequency controlling element in an audio oscillator which modulates the Minitrack transmitter. Two cores will be used in an orbital switching arrangement whereby the core that modulates Minitrack will contain the signal of the preceding orbit, while the second core will be storing the information from the current orbit. Switching will occur as the satellite emerges from dark to light.

The environmental studies in the satellite will include: (a) Measurement of the temperature of the internal instrument package by means of a thermistor. (b) Measurement of the temperature at two spots on the satellite shell, also with thermistors. (c) Measurement of erosion effects at four places on the satellite shell. This will be done with very thin resistance strips, although one of the measurements may be made with a cadmium sulfide cell. (d) Determination of whether or not the satellite shell is punctured by meteorites. This will be done by monitoring the pressure in originally pressure tight chambers forming two separate zones girdling the satellite shell. (e) Counting the micrometeorites that strike the satellite, using sensitive microphones.

The performance of these experiments is being done by the Naval Research Laboratory.

Group II: Cosmic rays and erosion measurements—The principal experiment in this group is the measurement of the cosmic-ray intensity as a function of position and time over the range of geomagnetic latitudes covered by the satellite. The plan is to use a geiger tube as the counter, to store the data on a magnetic tape recorder during a complete orbit, and then read out the information via the telemetering link at time of passage over a ground station.

Along with the cosmic-ray experiment, this group contains a micrometeorite bombardment experiment, using thin resistance strips on the surface of the satellite.

The State University of Iowa (SUI) was chosen to perform the cosmic-ray experiment with the Air Force Cambridge Research Center doing the micrometeorite bombardment measurement.

Group III: Earth's magnetic field and air density—The principal experiment in this group is that of determining the Earth's magnetic field above the ionosphere. There are three objectives: (a) To determine the existence or nonexistence of extraterrestrial currents such as the Størmer-Chapman ring current. (b) To obtain data on ionospheric currents giving rise to diurnal and irregular variations of the magnetic field, especially near the equatorial jet. (c) To improve our knowledge of the Earth's main magnetic field.

It is planned to use a three- to four-pound version of the Varian-type proton-precessional magnetometer in the satellite, including batteries for 50 days of operation at up to 50 readings per day. To obtain the information sought, the magnetic field measurements made in the satellite will be combined with measurements made simultaneously on the ground at the telemetering stations.

In this satellite experiment, the air density will be determined by its effect on a 30-inch diameter expansible sphere weighing about 0.7 pound to be ejected into the orbit from the main satellite at the time of separating the satellite from the empty third-stage casing.

The TPESP has chosen the Naval Research Laboratory to perform the magnetic field experiment, and the Langley Field Laboratory of the National Advisory Committee for Aeronautics to prepare the sphere for the air density measure-

ments. The actual determination of the densities will be made from optical observations of the motion of this sphere.

Group IV: (A) Radiation balance experiment—The purpose of this experiment is to determine the difference between the solar-energy influx to the Earth and the radiation efflux in the satellite's orbital belt, the central portion of which will be the tropical regions. To determine this radiation imbalance, the temperatures of four small spheres of differing absorptivities, mounted on arms extending from the satellite, and thus exposed to the radiations from the Earth and Sun, will be monitored. These temperatures, together with the equations defining the equilibrium temperatures of the spheres, will then permit one to deduce the radiation imbalance over the orbital belt.

(B) Cloud cover—The purpose of this experiment is to detect and plot out the distribution and motion of the clouds covering the portion of the Earth observable from the satellite in orbit. The planned approach is to use two infrared optical systems pointing in opposite directions along a diameter inclined at 45° to the spin axis of the satellite, with lead sulfide detectors. As the satellite spins the detectors will scan the surface of the Earth in a narrow strip normal to the axis of spin. Since the spin axis of the satellite will lie essentially in the orbital plane, the orbital motion of the vehicle will cause the strip scanned to move along over the Earth. The detectors should be able to differentiate between water, land, and cloud cover, and the data they provide will be radioed to the ground and recorded on magnetic tape. Then by analog techniques the data can be represented on a map of the Earth so as to show the actual position of the cloud cover. A series of such maps corresponding to progressively advancing times will give the motions of the cloud cover.

At the present time the final choice has not been made between Group IV (A) and IV (B). The University of Wisconsin, which proposed Group IV (A), was chosen to carry it out, and the U. S. Army Signal Engineering Laboratories, who proposed Group IV (B), were selected to prepare the equipment. Both experiments will be brought to flight stage, and the decision as to which will fly will be made at a later date.

PROGRESS TO DATE

Launching vehicle—The Earth satellite will be placed in an orbit by means of the Vanguard launching vehicle. This vehicle will be a finless, basically cylindrical three-stage rocket having an overall length of about 72 ft, a maximun diameter of 45 inches, and a launching weight of slightly over 22,000 lb. The first stage will be propelled by a pump-fed, liquid rocket engine using liquid oxygen and kerosene for its main propellants, and having a nominal, sealevel thrust of 27,000 lb. The second stage will be propelled by a pressure-fed, liquid rocket which will use white fuming nitric acid and unsymmetrical dimethyl-hydrazine as propellants. The third stage will be propelled by a solid rocket.

The first two stages will be guided and the third maintained in a fixed orientation while it is firing. The rocket will be attitude controlled, the first two stages by means of changing the direction of the thrust vector by deflection of the motors in their gimbal mounts, and by the use of jet reactors. The third stage will be maintained in the correct orientation during firing by giving it sufficient rotational energy prior to ignition of the solid rocket. Guidance will be by means of an inertial reference system which will be programmed by a rocket-borne sequence controller in which has been stored the prescribed tilt program prior to launch.

The rocket will be launched vertically at Cape Canaveral, Patrick Air Force Base, Florida, which has a latitude of 28° 28'N and will be programmed into a smooth curve tilting gradually in the direction, a little south of east, to give an orbit of 35° maximum inclination. The first stage will burn until its fuel is exhausted and will fall away as the second stage engine is ignited. After exhaustion of second-stage fuel, the rocket will coast until apogee is reached during which period the vehicle will be brought to the correct orientation for projection of the third stage. After the proper angular velocity has been imparted to the third stage, separation and ignition will occur.

Major guidance and control components have been manufactured and are being employed in controls system tests.

Launching facilities at Cape Canaveral have been constructed. Special launching fixtures and blockhouse monitors and controls will be ready for installation upon completion of Test Vehicle 1 (Viking #14) operations in the field.

An initial firing of Test Vehicle 0 (Viking #13) was successfully executed on December 8, 1956. This firing was employed to check out rocket borne and ground instrumentation required for the flight evaluation of test vehicles and to determine the readiness and suitability of launching facilities.

Radio tracking and telemetering—The NRL Minitrack system has been chosen for acquisition and radio tracking of the satellites. The Minitrack

system is a radio-phase comparison interferometer operating at 108.0 Mc. The tracking signal will also be amplitude modulated for telemetering the scientific data obtained from the satellite-borne detectors. The transistorized transmitter to accomplish this weighs 1¼ pounds, including the four antenna rods that will extend out from the satellite in flight. It uses about 7½ pounds of mercury-cell batteries for up to 3 weeks of continuous operation at 50 milliwatts output. For flexibility it has been arranged that telemetering may be either continuous or commanded. When commanded, a 12-ounce receiver, including power supply, in the satellite will be used to receive the command signal from the ground to turn on the telemetering circuits at the time of passage over a ground station. At the ground, the telemetering receiver will be separate from the tracking receiver, and will use its own tilting antenna system to increase the telemetering signal to noise ratio.

The production of the tracking equipment is now underway at Bendix Radio. Production of the tracking antennas is starting at the Technical Appliance Corp. Specifications for the tilting telemetering antenna, of 18 db gain, have been drawn up. Ten multiple bandwidth receivers of 3, 5, and 30 kc bandwidth, and a like number of 80 kc multichannel Ampex magnetic-tape recorders have been procured for the telemetering ground stations. Command transmitters for the telemetering ground stations are also under procurement. The first Minitrack tracking-telemetering transmitters have been built at NRL. A Minitrack test and evaluation station has been in operation at Blossom Point, near Washington, D.C., since July of 1956, and training courses in the operation of the Minitrack system are now being given. Stations in Fort Stewart, Georgia; Havana, Cuba; Quito, Ecuador; Lima, Peru; Antofagasta, Chile; Santiago, Chile; Antigua, British West Indies; and San Diego, California, are under construction, six of them by the U. S. Army. A station at Woomera, Australia, is at present in the planning stage.

Optical tracking—Responsibility for organizing and carrying out the optical tracking of the IGY satellites has been assigned by TPESP to the Smithsonian Astrophysical Observatory (SAO). A precision camera, of 20-inch aperture and 20-inch focal length, has been designed and is under construction by the Perkin Elmer Corp. A dozen or so sites located around the orbital belt have been selected for the satellite photographic stations and plans for putting them into operation are crystallizing.

SAO is also organizing a visual observing program under the name of Moonwatch. At various locations groups of amateur astronomers will use binoculars and low-power telescopes to search for the satellite. These instruments will be mounted in fixed positions so that their fields of view overlap and form a continuous fan across the sky from north to south. A large number of groups have already been organized in the United States, and these groups are holding learning and practice sessions. In addition some progress is being made in extending the program to other countries. Should the radio-tracking transmitter in the satellite fail, this visual observing net will be the means for acquiring the satellite for the photographic net.

Temperature control of the satellite—One of the most critical problems in operating an instrumented artificial satellite will be that of maintaining the temperature of the vehicle within acceptable limits. Parameters that affect this problem are the emissivity-absorptivity properties of the satellite's surface, the time the satellite spends in sunlight and the time in shadow during a revolution, the amount of heat generated within the satellite by electronic equipment, and the degree of thermal isolation of the instrument package from the satellite shell.

The NRL has been studying the properties of various surface coatings, making calculations of shell temperatures for all possible orbital conditions, determining both experimentally and theoretically the heat-flow regime in the interior of the satellite, and designing heat switches to control the rate of heat flow to or from the satellite instrument package. Simultaneously the Engineer Research and Development Laboratories (ERDL) at Ft. Belvoir have been developing techniques of coating the satellite shells with such things as silicon monoxide. A coating of silicon monoxide over an aluminum undercoating, for example, can be used to give high visibility together with any chosen ratio within a fairly wide range of absorptivity in the visible to emissivity in the infrared. On the basis of progress to date, it appears possible to keep the satellite package temperature within one degree of its equilibrium temperature and to locate that equilibrium temperature within ±20° of a selected value in the range from less than 0° to 80°C. The details of these studies are being written into a report and will be available to other satellite experimenters. NRL is also prepared to provide consultation on heat switch design and on the temperature control problem in general.

Thermal and vacuum testing—A facility has been

set up at NRL for the design and acceptance testing of the IGY satellites. A pre-prototype model of a Group I (that is, solar Lyman alpha and environmental) satellite with the instrument package has been tested at room temperature, 0° C, and 45° C, at a pressure of less than 0.1 micron of Hg. As was expected, transistor performance in this version became unsatisfactory and modulation of the telemetering transmitter was lost at the 45° temperature. Modifications are underway to yield a prototype for this group of experiments that will operate satisfactorily to at least 60° C instrumentation package temperature.

Vibration testing—A facility for design and acceptance testing of IGY satellites is being set up at NRL. A sinusoidal test facility is already in operation, and equipment for random vibration testing is expected to be in full operation by the summer of 1957.

The basic objective in the vibration testing program is to insure that the odds will be at least 20 to 1 that the satellite will survive the launching vehicle vibrations and accelerations in good operating condition. To achieve this the following program is specified: (1) Sinusoidal vibration tests over a frequency range of 10 to 2000 cps at levels up to 24 g (peak) for preliminary design testing. (2) Narrow band random noise vibration test over a frequency range of 20 to 2000 cps at levels up to 24.7 g (rms) for preliminary design testing. (3) Wide band (10 to 2000 cps) random noise vibration tests up to a level of 25 g (rms) for final design tests and tests of flight units. (4) Centrifuge tests up to 100 g in the thrust direction for preliminary and final design tests.

Over 175 sinusoidal interim design tests have been made on various satellite models, satellite components, and components of the Vanguard test vehicles, as of March 25, 1957.

Work on the narrow-band random-noise test equipment has now progressed to a point where we are able to offer this test as a substitute for the sinusoidal tests used to establish the adequacy of a design.

Work is continuing on the installation of the wide-band random-noise test equipment which will be used for final design tests and test of flight units. It is expected that this equipment will be sufficiently ready for use in time to conduct the first satellite final design test which started April 8, 1957.

Approximately ten centrifuge tests have been provided with a small vertical centrifuge at NRL, and one preliminary design test has been provided for a 20-inch satellite with a larger centrifuge at the Chesapeake Bay Annex of NRL.

Satellite simulator for visibility studies—A satellite simulator has been constructed that permits reproducing the satellite in magnitude and angular speed, with a sky background that is correct in brightness and star field, over the entire range of conditions to be encountered. Observations will be made with different observers and telescopes. Preliminary results were presented to the SAO in February 1957. It was reported that the $5\frac{1}{2} \times 50$, 8×48, and 20×120 telescopes are effective, very roughly, for 20-inch satellites to 500, 800, and 2000 mi respectively.

Satellite construction—Complete shells and internal structures are required for tests at NRL, for flights in test vehicles, and for preparing the finished flight version of the IGY satellites themselves. Aluminum test models have been built and assembled at NRL; magnesium units, at Brooks and Perkins in Detroit, Michigan. The outer coating of silicon monoxide required for temperature control, as described earlier, is put on the shell at ERDL.

To date, twelve of the 20-inch magnesium units for the Lyman alpha solar radiation and environmental studies satellite have been delivered. Because this set of experiments is the first one to be assembled, a fairly large number of the units is being prepared to provide enough units for a rigorous testing program, as well as for the final flight models. In the case of remaining experiments it is planned to build, for each, five complete flight units with the magnesium shells, two to be subjected to rigorous test, the other three to be readied for actual launching when the time comes.

Already extensive structural tests on the 20-inch units have been completed. Thermal and vacuum tests are continuing.

For layout work and preliminary testing, aluminum prototypes of the shells for the cosmic-ray and cloud-cover satellites have been built by NRL for the State University of Iowa and the U. S. Army Signal Engineering Laboratories respectively. Some preliminary design work has been done on the NRL magnetometer satellite, which may be the only IGY satellite to be non-spherical.

Satellite spin and separation from third stage—After burnout of the third stage, the satellite will be separated from the empty rocket casing with a differential velocity of about three feet per second. To accomplish this a special separation mechanism

has been designed and built. These mechanisms are completely self-contained interchangeable units, armed by acceleration of the third stage. The mechanisms, all of which have now been delivered, were built by the Raymond Engineering Laboratory at Middletown, Connecticut. Two mechanisms have been thoroughly tested for reliable operation under conditions of vacuum, vibration, acceleration, and temperature, and found satisfactory. The remainder of the mechanisms are being inspected carefully, and a number of caterpillar motors identical to those used in the mechanism are scheduled for even further testing.

Power supplies—Power supplies for the Group I experiments and the Minitrack tracking-telemetering transmitter have been designed using mercury cells. A variety of such cells is being tested in a vacuum of one to two microns of mercury at temperatures of 0°, 10°, and 60° C. Tentative results of these tests are that in an unpressurized condition 60° C is too severe a temperature, and that performance improves with decreasing temperature down to 0° C. Certain of the cells, of which the RM 520 cell is one, must be fixed, perhaps by completely sealing them, before they will be acceptable for use in the satellite. Overall indications are that a cool-running satellite will probably be safest for the Group I experiments as now designed.

The U. S. Army Signal Engineering Laboratories have been working on the development of a solar power supply for possible use in IGY satellites. An operating supply has been constructed and was flight tested twice in Aerobee-Hi's in April 1957. This unit weighs four ounces, occupies $3 \times 3\frac{1}{2} \times \frac{1}{2}$ inches, and furnishes three volts at 20 milliamperes. To produce this the sensitive area is about ten square centimeters. For a satellite, the mounting would probably be reduced in weight. SEL is now working on methods of attaching such solar units to the satellite. Work is starting on cycle life tests using silver-cadmium storage cells. Previous tests were made using silver-cadmium cells of about postage-stamp size, and indicated a life of 500 discharge-recharge cycles. With larger cells a much greater cycling life is anticipated.

The Group I satellite—A complete Group I preprototype satellite has been assembled and checked out electrically. The Lyman alpha ion chamber development is complete, and the manufactured tubes have been delivered. A complete evaluation of the system (ion-chamber electrometer circuit, telemetering modulator, and Minitrack transmitter) is now being carried out under environmental test conditions.

For the environmental studies, Victory Engineering Corp. thermistors have been selected and shown to have reproducible characteristics that are suitable for telemetering. The chosen thermistors are No. 32A12, with a resistance of 2000 ohms at room temperature, and a temperature coefficient of −4.6 pct per degree at 0° C. Chromium resistance strips for the erosion gages have been made by evaporation onto Pyrex glass. As constructed, the strips have an initial resistance of about 2000 ohms. It has been found feasible to increase the sensitivity of the gage to further erosion by pre-eroding the strip with an air-gun abrasive until its resistance rises to 20,000 ohms. Both the 2000-ohm and the 20,000-ohm pre-eroded strips will be used so as to provide for two ranges of sensitivity. A cadmium sulfide cell is also being evaluated for erosion study use. A 1½ ounce differential pressure gage has been received from the contractor, tested, and found acceptable. For the meteor counting, microphones of the barium titanate type, sensitive to impacts by particles of 2×10^{-8} ergs of energy, have been selected. A transistor amplifier and magnetic counter unit that continuously provides three decimal digits of the cumulative count of the impacts, has been fabricated in final form and is currently undergoing electrical tests. The unit weighs 3.1 ounces, and uses a TR133 mercury battery weighing 1.4 ounces.

A telemetering premodulator for this satellite has been designed to convert several input signals from the scientific detector units into a single electrical signal containing all the desired information. This single signal is then used to modulate the radio tracking carrier for relaying the information to the ground stations. The final version of the premodulator weighs about 6.5 ounces including power supply for four weeks of operation, provides for 48 channels of information on a time-sharing basis totaling 15 kc of bandwidth.

Associated with the premodulator is a storage and switching unit for use in obtaining the peak value of the Lyman alpha solar radiation encountered during each orbit. The unit consists of two separate memory sections, one of which is being read out to obtain the peak Lyman alpha value stored during the previous orbit, while the other is in the process of storing the peak value for the current orbit. As the satellite passes from the shadow part of its orbit into the sunlight, a switch activated by a silicon-boron solar cell reverses the

roles of the two memory units, at this time resetting the one that was being read out so that it can begin storing. The weight of the peak reader is 2.5 ounces, including the orbital switch. It uses one Mallory RM-12 battery weighing 1.4 ounces.

A complete prototype of the instrumentation for the Group I satellite, including the Minitrack tracking-telemetering transmitter, has been assembled and was flown in April 1957 in one of the Aerobee-Hi's in which the SEL solar power supply was checked.

The other IGY satellites—The other IGY satellites are in various stages of preparation, the SUI cosmic-ray unit being the only one nearing completion at the present time. There have been meetings at NRL to work out the shell and structure specifications for the different experiments, requirements to be placed on the Minitrack telemetering, and the design and acceptance testing program. The pace of the IGY satellite program being what it is, there should be much to report on all of these experiments in the not too distant future.

Acknowledgments—I should like to thank my colleagues at the Naval Research Laboratory for assistance in the preparation of this report, specifically: J. M. Bridger on the launching vehicle; R. Easton, radio tracking and telemetering; L. Drummeter and M. Schach, temperature control, thermal and vacuum testing, and battery tests; R. Blake, vibration testing; R. Tousey, satellite simulator, visibility studies, and optical tracking; L. Winkler, satellite construction, and spin and separation from the third stage; W. Matthews, telemetering, orbital switching, and micrometeorite counts; H. LaGow, environmental measurements; H. Friedman, Lyman alpha solar radiation; and J. P. Heppner, Earth's magnetic field.

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Some Comments on the Results Obtained with the Cambridge Pendulum Apparatus in North America

R. L. G. GILBERT

Abstract—The results obtained by the Dominion Observatory with the Cambridge pendulum apparatus in 1952 and 1953, while establishing a gravity base line from Mexico City to Fairbanks, Alaska, are analyzed with a view to improving their consistency. The analysis shows one pendulum to be much more stable than the other four, and results obtained from this pendulum are quoted. These are compared with the results published by the Dominion Observatory, and with those obtained by the Woods Hole Oceanographic Institution using the Gulf pendulum apparatus. An investigation into the behavior of the pendulums at other times is attempted, and tentative conclusions drawn which should prove valuable in the planning of future pendulum gravity surveys.

Introduction—A comparison between the values of gravity along the North American fundamental gravity base line obtained by the Dominion Observatory, using the Cambridge pendulum apparatus [*Garland*, 1953, 1955] and the Wood's Hole Oceanographic Institution, using the Gulf pendulum apparatus [*Rose* and *Woollard*, 1955], shows discrepancies as indicated in Figure 1. These discrepancies have given rise to a theory that the North American and British gravity calibrations may differ by about one part in 1000. The presence of differences of such magnitude along the primary base line is a matter for concern, and this paper shows some possible causes of error.

Analysis of the Cambridge pendulum results—The Cambridge pendulum apparatus used five Invar pendulums, which were swung in pairs: 1A with 1B, 1A with 1C, and 6B with 6C, each pair being swung two or three times. The mean period of each pair of pendulums is used for computing the results, so that the effect of ground movement on individual pendulum periods is removed so long as the two periods are nearly the same, and the ground movements not too severe. By comparing the consistency of the periods of one pendulum for its three swings at a given station [*Garland*, 1953, pp. 222–226] some estimate of the effect of ground movements on its period may be obtained. This assumes that the other errors involved are small. In the work under consideration it was noted that the spread in the periods of one pendulum was frequently far greater than that of its mate. Pendulums 1A and to a lesser extent 6B showed this effect, and it is unfortunate that all published results are dependent on the periods of one or the other of these pendulums. The large spread in the readings of these pendulums is evidently caused by effects other than ground movements, as the latter would have an equal, though opposite, effect on each pendulum of a pair.

In 1952 the stations at Ottawa, Beloit, and Houston were occupied more than once, and the difference in the values of mean periods for successive occupations at these stations was compared with the spread in the individual sets of periods (Table 1). The results of Pendulum 1A were divided into two groups, depending on whether it was swung with 1B or 1C. The periods given in the tables are in units of 10^{-7} sec, and one unit is equivalent to about 0.4 mgal. The mean period for example of Pendulum 1A, swung with 1B at Ottawa on July 17, 1952 was 506,3955.7 units. This was the mean of two swings which had an rms (root mean square) spread of 0.2 unit. Similarly the mean period of the same pendulum at Ottawa on October 21, 1952 was 506,3958.0, and the rms spread 0.5 unit. The overall mean of these two values is 506,3957.0 units, and the rms difference between the two values above and their mean is 1.2 units. The figure quoted in Row 11, under the heading 'mean rms difference,' is the rms mean of the differences between the overall means and the mean periods of the several sets of swings at the three stations listed. The figure quoted in Row 11 under average rms spread is the average of the rms spreads tabulated above.

Of all the pendulums, only 1B gave results which repeated within the order of accuracy expected from the mean internal accuracy of the several sets of swings, with a mean rms difference of 0.6 unit for the reoccupied station values, and 0.8 unit for the average rms spread. Pendulums 6B and 6C had differences of 1.6 units for the reoccupied station values, but only 1.1 and 0.8 units respectively for the internal consistency. Pendulums 1A and 1C

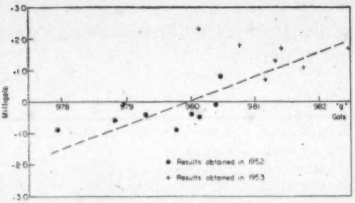

FIG. 1 – Difference between Cambridge and Gulf Pendulum results, with a possible systematic trend indicated

were still worse. The analysis was repeated with the 1953–54 results and showed precisely the same effect. The effect of ground movements always appears to be less than one unit, or 0.4 mgal.

From this, it might appear reasonable to assume that Pendulum 1B is stable, while the others are not. Recalculation of the results, using only the periods of this one pendulum indicates that some of the previously adopted gravity values must at least be treated with reserve. The results from Pendulum 1B are tabulated in Table 2, together with the probable error at each station, judged by the consistency of the several sets of observations at the stations which were repeated, the number of separate swings of the pendulum at the station under consideration, and their internal consistency. The value of g at the Ottawa pier is assumed to be 980.6220, as in Garland's work.

A recent communication from Rose has given revised values for the Gulf K & M results at some stations (Table 3). They agree with the results obtained from all the Cambridge pendulums with an rms difference of 0.8 mgal, with the results of the Cambridge pendulums 6B and 6C with an rms difference of about 0.8 mgal, and with the results from 1B with an rms difference of 0.7 mgal. Figure 1 has shown the origin of the theory that the American and British Gravity standards differ. However, Figure 2 shows an alternative explanation. The stations from Mexico City to Winnipeg were observed in 1952, using Beloit as a sub-base; the others were observed in 1953 and used Edmonton as a sub-base. If the adopted values for the two sub-bases are in error, then the ordinate line should be broken as shown. It is notable that

TABLE 1 – *Periods of individual pendulums*

Row	Station	Date	Pendulums											
			1A				1B		1C		6B		6C	
			Swung with 1B		Swung with 1C									
			Mean period	Rms spread	Mean period	Rms spread	Mean period	Rms spread	Mean period	Rms spread	Mean period	Rms spread	Mean period	Rms spread
1	Ottawa	1952 July 17	506,3955.7	0.2	506,3960.3	3.8	506,3993.6	0.4	506,3967.9	0.4	505,6122.0	2.4	505,6091.4	1.5
2		Oct. 21	6,3958.0	0.5	6,3956.6	0.5	6,3993.5	0.7	6,3963.2	1.4	5,6124.5	0.6	5,6090.7	0.3
3		Overall mean	6,3957.0	...	6,3958.5	...	6,3993.5	...	6,3965.6	...	5,6123.1	...	5,6091.1	...
4	Beloit	Aug. 1	6,5567.2	0.8	6,5566.3	0.5	6,5602.2	0.9	6,5574.6	0.9	5,7723.5	0.4	5,7698.8	0.4
5		Sep. 6	6,5566.6	1.4	6,5565.2	0.9	6,5602.1	0.7	6,5573.4	0.9	5,7728.4	0.3	5,7703.0	0.7
6		Sep. 21	6,5566.0	1.1	6,5564.8	0.4	6,5601.3	0.6	6,5573.7	1.3	5,7730.1	1.1	5,7700.0	0.6
7		Overall mean	6,5566.6	...	6,5565.4	...	6,5601.9	...	6,5573.9	...	5,7730.3	...	5,7700.6	...
8	Houston	Aug. 9	6,7383.3	0.8	6,7383.7	0.5	6,7414.7	1.1	6,7385.5	0.4	5,9540.5	0.3	5,9508.4	[a]
9		Aug. 29	6,7377.3	[a]	6,7377.1	1.4	6,7312.5	[a]	6,7385.8	0.3	5,9535.3	1.1	5,9506.4	0.0
10		Overall mean	6,7381.1	...	6,7380.4	...	6,7413.9	...	6,7385.7	...	5,9537.9	...	5,9507.2	...
			Mean rms difference	Average rms spread	Mean rms difference	Average rms spread	Mean rms difference	Average rms spread	Mean rms difference	Average rms spread	Mean rms difference	Average rms spread	Mean rms difference	Average rms spread
11			2.0	0.9	2.6	1.7	0.6	0.8	2.0	0.9	1.6	1.1	1.6	0.8

[a] Only one swing was made at these stations.

TABLE 2 – *Comparison between results from Cambridge and Gulf Pendulums, (Ottawa—980.6220 gals)*

Station	Dominion Observatory			Woods Hole	Pendulum 1B – all Cambridge	All Cambridge – Gulf	Pendulum 1B – Gulf
	Cambridge Pendulum 1B	Estimated probable error	All Cambridge pendulums	Gulf M & K results			
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	gal	mgal	gal	gal	mgal	mgal	mgal
Mexico City	977.9429	0.3	977.9415	977.9424	+1.4	−0.9	+0.5
Monterrey	978.8058	0.6	978.8055	978.8061	+0.3	−0.6	−0.3
Houston	979.2989	0.4	979.2990	979.2994	−0.1	−0.4	−0.5
Tulsa	979.7666	0.3	979.7664	979.7673	+0.2	−0.9	−0.6
Beloit	979.9995	0.2	979.9990	979.9994	+0.5	−0.4	+0.1
Washington (1)[b]	980.1198	0.3	980.1193	980.1198	+0.5	−0.5	0.0
Madison	980.3709	0.3	980.3696	980.3697	+1.3	−0.1	+1.2
Huron	980.4550	0.3	980.4555	980.4547	−0.5	+0.8	+0.3
Winnipeg	980.9941	0.3	980.9952	...	−1.1	...	...
Washington (2)[b]	980.1209	0.4	980.1221	980.1198	−1.2	+2.3	+1.1
Lethbridge	980.7600	0.3	980.7612	980.7594	−1.2	+1.8	+0.6
Winnipeg	980.9936	0.6	980.9952	...	−1.6	...	...
Red Deer	980.9985	0.3	980.9988	...	−0.3	...	...
Edmonton	981.1684	0.2	981.1691	981.1684	−0.7	+0.7	0.0
Grande Prairie	981.3187	0.3	981.3195	981.3182	−0.8	+1.3	+0.5
Fort St. John[a]	981.4073	0.3	981.4077	981.4060[a]	−0.4	+1.7[a]	+1.3[a]
Fort Nelson	981.6863	0.4	981.6832	...	+3.1	...	...
Watson Lake	981.7158	0.3	981.7165	...	−0.7	...	...
Whitehorse	981.7487	0.3	981.7502	981.7491	−1.5	+1.1	−0.4
Snag	981.9340	0.5	981.9339	...	+0.1	...	...
Fairbanks[a]	982.2470	0.4	982.2477	982.2460[a]	−0.7	+1.7[a]	+1.0[a]
Teddington	981.1981	0.2	981.1989	...	−0.8	...	...
Rms difference					1.1	1.0	0.7
Mean difference					−0.2	+0.4	+0.2

[a] Correction applied to convert the readings of the two sets of equipment to the same site is somewhat uncertain.

[b] Commerce Building Pier.

the comparison shown in Column 8, Table 2, and Figure 3 does not show any appreciable trend or discontinuity, nor do the comparisons in Columns 6 or 7 in Table 3, as the sets of results for Pendulum 1B and the revised Gulf values are both related to a single base for the whole range of observations. The revised Gulf Results are based on a value of g at Edmonton of 981.1684 while all the results from the Cambridge pendulums are based on g at Ottawa of 980.6220. It appears that one of these values is in error, as Columns 8 and 9 of Table 3 (where a correction term has been applied to the differences between the several sets of values) indicate better agreement between the values than do Columns 6 and 7 of Table 3. This strengthens the evidence of Figure 2 that erroneous values of g have been given to the sub-bases.

The use of sub-bases, common to both the Cambridge and Gulf surveys, introduces an unnecessary error which may be removed, admittedly at a certain cost, by returning to the National Base fairly frequently. The stations used by the two surveys are regrettably often at different sites and are not directly comparable; care should be taken to prevent this happening.

Washington was visited in both 1952 and 1953. The two values derived from all the Cambridge pendulums differ by 2.8 mgal while the two results derived from pendulum 1B differ by 1.1 mgal, which supports the belief that 1B is the most reliable of the Cambridge pendulums.

I have attempted to check the behavior of the Cambridge apparatus in recent years, using published results from other surveys. It is regrettable that, on the whole, very few stations have been occupied more than once during the course of other surveys. However, in the 1950 South African survey [*Hales* and *Gough*, 1950], pendulum 1B does not appear to be appreciably better than the other five, but this conclusion is only based on the results at the two bases.

Conclusions and suggestions for future pendulum

TABLE 3 – *Comparison between Cambridge and revised Gulf values*

Station	Woods Hole		Dominion Observatory		Pendulum 1B – revised Gulf	All Cambridge – revised Gulf	Col. 6 – 0.8	Col. 7 – 0.6
	Gulf (55–44)	Revised Gulf based on Edmonton g 981.1684 gal	All Cambridge	Pendulum 1B				
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	gal	gal	gal	gal	mgal	mgal	mgal	mgal
Fairbanks[a]	982.2460[a]	982.2478[a]	982.2477	982.2470	−0.8[a]	−0.1[a]	...	...
Whitehorse	981.7491	981.7490	981.7502	981.7487	−0.3	+1.2	−1.1	−0.6
Fort St. John[a]	981.4060[a]	981.4056[a]	981.4077	981.4073	+1.7[a]	+2.1[a]	...	...
Grande Prairie	981.3182	981.3179	981.3195	981.3187	+0.8	−0.2	0.0	−0.8
Edmonton	981.1684	981.1684	981.1691	981.1684	0.0	+0.7	−0.8	+0.1
Lethbridge	980.7594	980.7594	980.7612	980.7600	+0.6	+1.8	−0.2	+1.2
Huron	980.4547	980.4536	980.4555	980.4550	+1.4	+1.9	+0.6	+1.3
Madison	980.3697	980.3690	980.3696	980.3709	+1.9	+0.6	+1.1	0.0
Beloit	979.9994	979.9987	979.9990	979.9995	+0.8	+0.3	0.0	−0.3
Houston	979.2994	979.2986	979.2990	979.2989	+0.3	+0.4	−0.5	−0.2
Monterrey	978.8061	978.8052	978.8055	978.8058	+0.6	+0.3	−0.2	−0.3
Mexico City	977.9424	977.9423	977.9415	977.9429	+0.6	−0.8	−0.2	−1.4
Rms difference					1.0	1.1	0.6	0.8
Mean difference					+0.6	+0.7	−0.1	−0.1

[a] Correction applied to convert the readings of the two sets of equipment to the same site is somewhat uncertain.

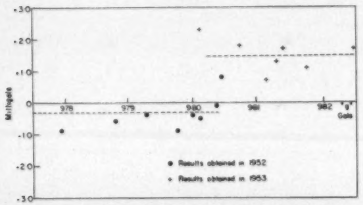

FIG. 2 – Difference between Cambridge and Gulf Pendulum results, with a possible discontinuity indicated

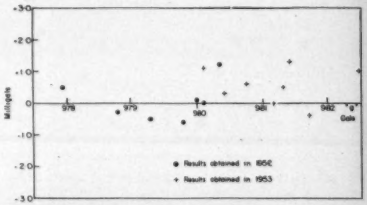

FIG. 3 – Difference between results from Cambridge Pendulum 1B and Gulf Pendulums, showing no trend or discontinuity

surveys—In general, the accuracy of pendulum observations has been based on the internal consistency of the sets of swings. I feel this to be unrealistic, as no account is taken of jumps or changes in the periods of the pendulums when transported from place to place, or of errors in measuring and applying corrections for temperature, pressure, and so on. I consider it to be very desirable to repeat several stations of a pendulum survey, and, if possible, repeat them several times; but especially to return to the primary base frequently during the survey. This procedure would be well advised no matter how the results are analysed.

It is possible for the divider circuits of the crystal frequency standard used to measure the pendulum periods to operate erratically; a simple electronic device may be constructed to check the 1000 c/s output, and should always be used during an observation.

I hope that the Gulf records may be analysed in a manner similar to that which I have suggested, and a comparison made between the results obtained from their best pendulum, and those from the Cambridge Pendulum 1B.

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Discussion

G. D. Garland (University of Alberta, Edmonton, Alta.)—The problems discussed by Gilbert in connection with pendulum measurements, especially those related to changes in pendulum periods are certainly very real. It is questionable, however, whether the method recommended in this paper, that is, the neglecting of the measurements made with four out of the available five pendulums is the proper approach. While we know very little about the causes of these random changes in period, they have certainly been recognized for a very long while. The noteworthy feature of the data summarized in Table 1 is not that the rms change in period at repeat stations is larger than the spread at any one station, but rather that it is not even greater, considering the excursions of several thousand miles by motor vehicle between repeat observations. It is true that Pendulum 1B repeats 'better' than the others, but this is by no means proof that it is inherently more stable, or that the other observations should be neglected. If we consider the repeat observations at Ottawa, the changes in period, in units of 1×10^{-7} seconds, between July 17, 1952 and October 21, 1952 are

Pendulum:	1A	1B	1C	6A	6B
Change:	2.3	−0.1	−4.7	2.5	−0.7

The mean change is −0.1 unit, the standard deviation of an individual measure of change is 2.92 units. The application of Chauvenet's criterion indicates that the results of an individual pendulum should not be rejected unless the change in period is outside the range −4.8 to 4.8 units. The problem of the rejection of observations arises in many fields of the physical sciences, but experience has shown that it is unwise to reject an observation unless it clearly lies outside the range provided by some acceptable criterion. This is evidently not the case here.

In considering the accuracy of the original observations, the standard deviation of a measurement of gravity at a station occupied only once was determined from the difference in the two values obtained with the pendulums of Set 1 and those of Set 6 respectively. These values were quite independent, as far as changes in pendulum periods were concerned, each depending on its own set of base swings, although the same timing standard was used for both sets. It is therefore not quite true to state that "no account is taken of jumps or changes in the periods of the pendulums when transported from place to place," in determining the limits of error in final values. On the other hand, I do not see how it is possible to arrive at a reasonable estimate of the standard deviation of a single observation by Gilbert's method of using only one pendulum, since that one pendulum is assumed *a priori* to be 'stable,' and to not change in period between base swings.

Finally, the fact that the values obtained with Pendulum 1B alone are apparently in better agreement with the Gulf pendulum values cannot be accepted as a reason for adopting it alone. It is the unbiased results, with nothing rejected except for obvious cause, obtained with the two types of pendulum apparatus which must be analyzed for traces of systematic departures. In particular, I should strongly oppose combining the results of the 'best' Cambridge pendulum with the 'best' Gulf pendulum in order to obtain a set of gravity standards.

Apparent Diurnal Variations of Arctic Stratospheric Temperatures

ARTHUR D. BELMONT

Abstract—The diurnal variations of radiosonde temperature data for Narsarssuak (BW-1), Greenland, from 1946–1948 are inspected and compared with data for Thule, Alert, Eureka, and Resolute. Observations were taken at BW-1 at local noon and midnight. In winter and spring the stratospheric temperatures there show a tendency for the difference, noon minus midnight, to diminish or even become negative. Similar patterns for apparent night warming in the lower stratosphere are found also at the other stations. The eight years of more recent and reliable arctic data which now exist should be made available to help determine the reality of this anomaly. Adiabatic semi-diurnal vertical motions required to produce the observed night warming amount to 1 or 2 cm/sec. It is suggested that atmospheric tides may be a contributing cause.

Preface—The basic paper of which this is an extract was completed in 1953, but because the unusual results were based upon only a very small sample of data, publication has been delayed in the hope of verifying the conclusions with some of the additional eight years of upper-air data now in existence for the stations used. Unfortunately, the author has been unable to procure summaries of more recent data. The imminent advent of the IGY makes it desirable now to acquaint those who are interested in the upper-air temperature field with these results, in the hope that the effects suggested here may be examined more carefully than has been possible until now.

The following includes only a discussion of the apparent diurnal temperature changes; seasonal variations will be the subject of a separate paper. The original paper contains an appendix with tabulations of data and sunrise-sunset and solar altitude computations.

Introduction—Narsarssuak, Greenland, 61°11′N, 45°25′W, hereafter called by its usual name, BW-1, is located at the southern tip of Greenland. In the years 1946–1948, it was one of very few stations where the standard radiosonde observations scheduled for 03h 00m and 15h 00m GMT were taken at local midnight and local noon.

There does not appear to be any previous investigation of average upper-air diurnal temperature variations for polar stations, although several studies have been made for other latitudes. The papers of *Penner* [1948], *Elsasser* [1940], *Scherhag* [1948], and *Möller* [1935] are concerned mainly with tropospheric levels in mid-latitudes. In general, they find night cooling of about 1°C/day. *Wexler* [1950] using pre-war data finds almost no diurnal change to 30 km. *Kay* [1951] found stratospheric values which gave about 1.2°C/day cooling at levels from 80 to 150 mb. He concludes also that observed daylight heating was too great to be caused by radiation and must either have been due to instrumental error or to dynamic causes.

Wulf [1946] determined that a diurnal temperature difference large enough to be observed does exist, although his data did not permit its measurement. This is based on the fact that if the observed diurnal changes are due only to direct instrumental heating, the difference in the day-night temperatures should continually increase with height. Since his data showed all types of variable increases and decreases, he concluded that some other factor than pure insolational instrumental heating was present.

Richl [1947], using a special series of three-hourly ascents, found midnight to noon warming at all levels, amounting to 2.6°C at 100 mb in the Caribbean, even after applying instrumental radiation corrections, and attributes it to non-adiabatic processes. *Scrase* [1954], concluded that radiation errors in the British radiosonde could account for all of the observed differences between day and night up to 15 km. Above that height real diurnal variations seem to exist and were estimated over Britain, in spring and autumn, at about 1.5°C at 55 mb, and 3°C at 25 mb.

Data—The complete data available for BW-1 are listed in Table 1. It will be noticed that four observations a day were not started until February 1948 and that the times of observation were set back one hour (04h 00m to 03h 00m GMT, etc.) starting in April 1948. For convenience in this preliminary study it was assumed that mean diurnal temperature variations obtained from the six-hourly observations were unaffected by this change. December 1947 data, as well as data for several hours in other months are missing. All

TABLE 1 – *BW-1 data available for the period 1946–1948, GMT*

Month	1946	1947	1948
	h	h	h
Jan.	04, 16	04, 16	04, 10, 16
Feb.	04, 16	04, 16	04, 10, 16, 22
Mar.	04, 16	04, 16	04, 10, 16, 22
Apr.	M, 16	04, 16	03, 09, 15, 21
May	—, 16	04, 16	03, 09, 15, 21
June	04, 16	04, 16	03, 09, 15, 21
July	04, 16	04, 16	03, 09, 15, 21
Aug.	04, 16	04, 10, 16	03, 09, 15, 21
Sep.	04, 16	04, 10, 16	03, 09, 15, 21
Oct.	04, 16	04, 10, 16	03, 09, 15, 21
Nov.	04, 16	04, 10, 16	03, 09, 15, 21
Dec.	04, M	M, M, M	03, 09, 15, 21

M Indicates data missing.
— Indicates observation not taken.

BW-1 data have been taken from photostats of the original radiosonde monthly summary sheets (Form WBAN-33).

The only other arctic stations for which data were available are given in Table 2.

For all these stations the published data are confined to monthly mean values at the two observation hours, 03h 00m and 15h 00m GMT. The radiosonde instrument used at BW-1 was a U. S. Air Force model. The instrument used at Thule was the U. S. Weather Bureau type, while at the joint Canadian-U. S. stations the same U. S. model was probably used during most of the periods listed in Table 2.

Data reduction—Because of the small and incomplete sample, usual statistical refinements were postponed to the time when more complete and reliable data and possible estimates of the instrumental radiation error became available. Only an approximate idea of the quantities involved was expected from this study.

Ideally, to compute semi-diurnal variations, one should find the difference of the noon observation from the mean of the observations taken at the previous and following midnight, thus eliminating the effect of day-to-day changes. This requires a continuous series of observations, however, and when all observations are available, it is simpler and as significant to take differences only between the monthly means of each hour, for this also eliminates day-to-day changes. When the observations are very erratic and fragmentary, as for BW-1, the number of noon-midnight pairs is very small and the occurrence of midnight-noon-midnight sequences almost negligible. Large individual temperature changes amounting to 20°C or more, of the type discussed by *Scherhag* [1952], occasionally occur between twelve-hourly values. Since a single very large individual change can greatly overshadow the mean of the handful of normal, small diurnal changes, the use of a few twelve-hourly differences is unsatisfactory. When the observations are so incomplete, a larger and possibly more satisfactory sample can be attained by using the entire set of values for each hour for the month. Thus, only mean monthly values of noon and midnight temperatures for the entire three year period were used to estimate noon-midnight variations.

Although four observations a day were scheduled at BW-1 for most of 1948, there were too few days per month when all observations were taken to be able to draw valid conclusions concerning diurnal changes at 06h and 18h LST. To overcome this scarcity, the original paper presented the data by season, but the results are of too little interest to reproduce here.

For all the other stations used, only monthly mean data for 03h and 15h have been published, hence there was no possibility of any more careful study. It should be noted also, that the local time

TABLE 2 – *Published arctic data*

Station	Location	Period	Reference	Local solar time of observation at 03h 00m, 15h 00m GMT
				h m
Thule	76°33′N 68°49′W	Oct. 46–Dec. 49	*U. S. Weather Bureau* [1950]	10 24 22 24
Alert	82°30′N 62°20′W	Sept. 50–Dec. 53	*Canada Met. Div.* [1955]	10 52 22 52
Eureka	80°1′N 85°39′W	June 47–Dec. 50	*U. S. Weather Bureau* [1951a]	09 16 21 16
Resolute	74°41′N 94°54′W	Nov. 47–Dec. 50	*U. S. Weather Bureau* [1951b]	08 40 20 40

of observation at Alert, Thule, Resolute and Eureka is from one to three hours earlier than at BW-1.

Radiosonde temperature data taken with the earliest instruments should not be included with data from later instruments in any careful future study of temperature variations. In the former types the heated shield probably had a relatively large radiation effect on the inner temperature element. Temperatures measured by later elements such as the exposed white thermistor described by *Brasefield* [1948] are considered much more accurate with respect to radiation effects at levels up to 80,000 ft, about 20 mb. However, this type of element was not likely in use at BW-1 from 1946 to 1948. At all the other stations, a U. S. Weather Bureau instrument with shielded thermistor was used. Only Alert data appear to have been subjected regularly to the table of corrections for radiation error, issued by the U. S. Weather Bureau about March 1950. Since the published records for Resolute and Eureka extend to December 1950, they may include about half a year of corrected data.

With the above exceptions, radiation errors doubtless existed when the instrument was in direct sunlight. To help determine solar position during the ascents, tables of sunrise and sunset, and of solar altitude at noon and midnight for BW-1 and Thule, to heights of 146,000 ft were computed and are presented in Appendix A of the detailed report [*Belmont*, 1954]. At BW-1, midnight is always in darkness, and noon is always in sunlight throughout the year. At Thule, on the average for levels to 50 mb, midnight is sunlit from late April to late August, and noon is dark from about mid-November to mid-February.

Another important error which must be considered is the preferential selection of warm ascents at highest levels due to premature bursting of balloons at cold temperatures. This will be discussed further below.

Diurnal variations—Figure 1 shows the variation with height of the temperature difference for local noon minus midnight at BW-1 and also the absolute range of the four daily temperatures. All values here are simply three-year means for each of the possible observation hours. In the warmer half year the noon values are generally warmer than at midnight at all months and levels, decreasing with height from about 4°C at the surface to a fraction of a degree in the lower troposphere and then increasing upward into the lower stratosphere to as much as 4°C at 100 mb. There is in general less diurnal difference between these two hours during the cold seasons, and the variations are comparable in magnitude to values given by *Kay* [1951] and *Riehl* [1947].

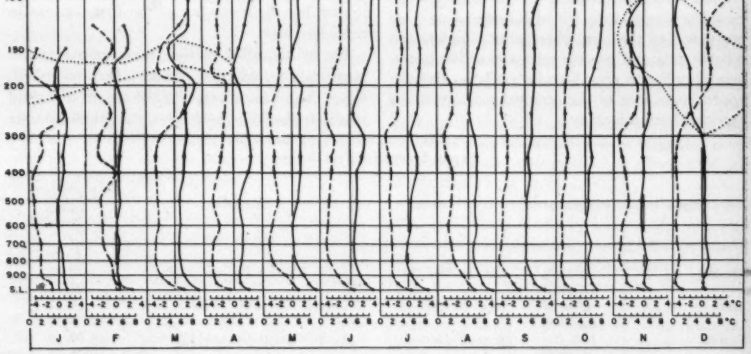

FIG. 1 – Average variation of diurnal temperatures at BW-1, Jan. 1946–Dec. 1948; solid curve and upper scale represent local noon minus midnight; broken curve shows observed maximum diurnal range on lower scale; dotted curve encloses regions of night warming

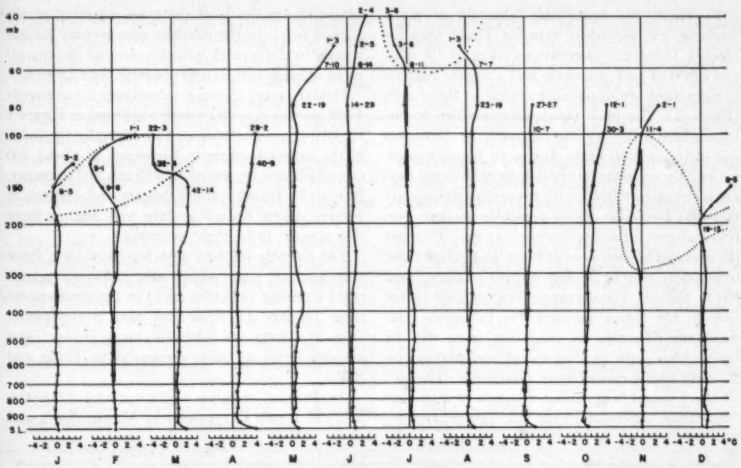

FIG. 2 – Average variation of 10h 00m–22h 00m LT temperatures at Thule, Oct. 1946–Dec. 1949; values are total observations: day–night

However, noticeable exceptions to the generally warmer noon soundings seem to occur in winter in the lower stratosphere. Here a fairly regular pattern of night warming, or at least a diminishing of the day warming, is apparent. These regions are lightly outlined in Figure 1 as are similar ones for Thule in Figure 2. Thus, at BW-1, midnight values seem to be as much as 2 to 4°C warmer than at noon in the stratosphere in November and December. At Thule, night warming also amounts up to 4°C in February and March.

As to the sources of error mentioned above, it should be noted that with respect to diurnal variations, the balloon bursting effect is of importance only in those months when night and day ascents are taken alternately in darkness and sunlight, and that at these seasons the instrumental radiation error probably has a much stronger tendency to create warmer ascents at noon. Thus the selection of ascents which favors warm night soundings due to balloon bursts in coldest temperatures is offset by the daytime insolational heating of the instrument which causes noon soundings to be too warm. Hence any apparent night-warming values which are found must be considered as minimum amounts which appear despite the probably large instrumental heating error of the noon ascents. In months of constant night or constant daylight, there are no appreciable diurnal effects from the two sources of possible error considered here. Thus, regardless of latitude or season, there should be a tendency for noon rather than night temperatures to be warmer, assuming the daytime direct insolational heating of the instrument overbalances the effect of the selection of warmer ascents at night due to balloon freezing.

An example of the direct heating which can occur with an unshielded white temperature element, has been given by *Bindon* [1956]. Using a pair of unshielded bimetal elements, one white and the other black, he computed the true temperature and found the white element correctly recorded ambient temperature up to 500 mb, but that it read from 0.6°C too warm at 400 mb to 4.8°C too warm at 40 mb. *Scrase* [1954] estimated the radiation error of the Meteorological Office radiosonde with a shielded element, for a solar altitude of 40°, as increasing from about 1°C at 500 mb to 5°C at 50 mb. Harmantas and Hodge, as quoted by *Riehl* [1947], estimated temperature corrections at about 100 mb, in the San Juan standard atmosphere, ranging from 1.5°C at a solar altitude of 30°, to 3.0°C at 50°, for the shielded U. S. Weather Bureau instrument used in 1944. At noon on June 21, the solar altitude is 52° at BW-1, 37° at Thule, and 31° at Alert.

To check the remarkable anomaly of night warming, the published data for Thule were inspected. Using the observations taken at 10h 00m and 22h 00m LST, we again find a similar pattern of night time stratospheric warming in the winter (Figure 2). The most outstanding feature in the troposphere is the daytime maximum in the spring and early summer. From August to January there is virtually no temperature difference between day and night up to 400 mb, with the unexpected exception that December shows relatively warmer day temperatures, although the Sun is at least 7° below the sea-level horizon even at noon. In February the troposphere may be slightly warmer at night from 800 to 350 mb. The maximum tropospheric variations in the spring are probably caused by the maximum difference in insolation from day to night which occur at that season and perhaps to the early spring maximum in total ozone. The latter effect would help explain the lack of a similar temperature difference in the fall. The general increase in amplitude of the noon warming at the highest levels in the daylight months may be due mainly to the greater radiation error in the instrument at noon and to fewer observations at night.

Similar layers showing a tendency for apparent night warming, such as were suggested in Figure 1 for BW-1, are also indicated at Thule by the bulge in the curves starting in November at about 300 mb which can be traced to 250 mb in December, 200 mb in January and February and 150 mb in March. Above 60 mb in July and August there also appears to be night warming.

The recently released data for Alert for a three and one-half year period also show springtime night warming (23h 00m LST) in the stratosphere from January to April and also in September (Fig. 3). There are relatively many observations at high levels at Alert compared to Thule and BW-1.

At Eureka, definite night-warming (21h 00m LST) of 1 to 2°C appeared in March, April, and

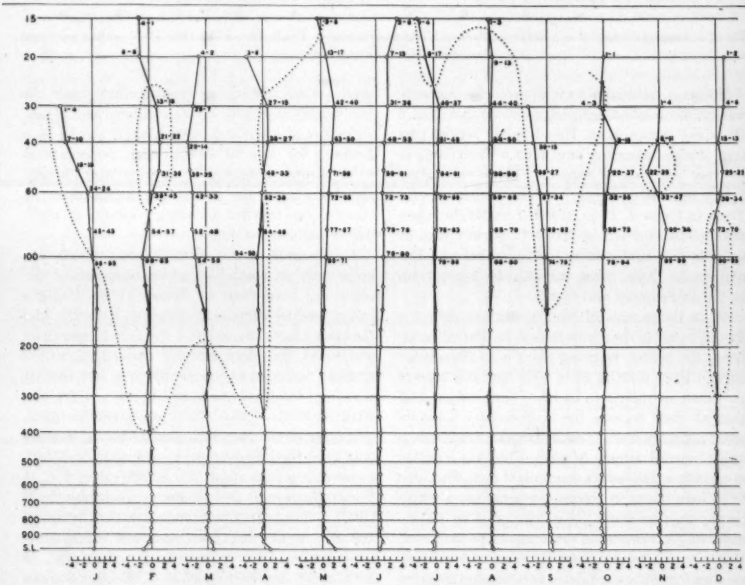

FIG. 3 – Average variation of 11h 00m–23h 00m LT temperatures at Alert, Sep. 1950–Dec. 1953; values are total observations: day–night

August at levels above 300 mb. At Resolute, night-warming (21h 00m LST) is found in the stratosphere in every month except August. Further, from January to May there is weak but regular night warming even in the troposphere.

Any real diurnal variations will be affected by systematic and random errors due to variations in observing technique, time of observation, synoptic conditions, and instrumental errors. But if we can assume that the sample is large enough to subdue the random variations, and that there are no systematically caused errors, then in certain months, depending on the station, there seems to be residual night-warming in the lower stratosphere of 1 to 2°C.

Discussion—These results are based on temperatures of constant pressure surfaces due to the present style of radiosonde summarization, but it may be well to consider what differences might appear if temperatures were measured at constant heights. Since

$$\left(\frac{\partial T}{\partial t}\right)_h = \left(\frac{\partial T}{\partial t}\right)_p + \omega_p \gamma$$

where γ is the actual lapse rate and is considered positive if temperature decreases with height, and ω_p is the vertical motion of the pressure surface (positive if upward), then the change at fixed height will be larger than at constant pressure if lapse rates are positive and if pressure surfaces are higher at noon than at night. Since we are dealing with the stratosphere, however, no assumption can be made concerning lapse rate since even its sign may vary. Nor can we there anticipate whether a selected pressure surface is higher, in the monthly mean, at day or at night. Thus the amount and even the pattern of diurnal temperature change at constant height might be slightly different from that at constant pressure.

Using extreme values for ω_p and γ in the stratosphere, over a 12-hr period, we estimate as a reasonable maximum difference in the two methods $\pm$ 1°C/12 hr, taking into account estimates for the standard deviations and correlation between ω_p and γ. In practice, however, the sign of the difference is often obvious from inspection of the plotted soundings when the stratospheric lapse rates are quasi-isothermal, and the difference between the two methods is normally very small, perhaps 0.1 to 0.2°.

If we are willing to accept the possibility that the apparent night warming is indeed real, we can imagine it being caused by diurnal vertical motions and non-adiabatic effects. The general atmospheric subsidence required to produce any of the stratospheric warming reported would correspond to a mean movement of about 1 or 2 cm/sec. Since the warming effect appears to be widespread, although of unequal intensity in space and time, some combination of semi-diurnal atmospheric tidal effects might appear a reasonable physical explanation, despite the general weakness of such tides in the polar regions [*Haurwitz*, 1956]. Although night warming is observed principally in dark months, this may be due only to the masking of the night-warming effect by the relatively stronger noon insolational heating of the warmer months. Thus, a tidal effect could operate at all seasons and be observed only when other influences were sufficiently weak. This may also lead us to expect that the night-warming effect can be noticed only in high latitudes when direct insolation at noon is weak. To our knowledge, no similar, warmer night temperatures have been found with temperate latitude radiosonde data.

Another physical explanation might be imagined as the diurnal effects of refraction and multiple scattering of radiation which can produce sensible heat through the atmosphere, but there seems to be general agreement among the specialists consulted that such effects are most unlikely to contribute significantly to the diurnal changes in temperature of the magnitude which has been observed.

From a statistical viewpoint the night-warming effect cannot be considered real, and is likely only due to the very small number of values used, the difference in the sample for day and night, and the fact that pairs of observations seldom existed for individual days. Attempts to verify the results by more careful analysis of the existing material invariably led to the conclusion that there were too little really comparable data. For example, nothing revealing was gained by analysing each individual ascent which contributed to a warm mean value at night at some upper level. At times this ascent was warmer and at times colder than either the sounding made 12 hours later or the mean ascent for the month for that hour. Further, a night ascent which is warmer than the noon one in the stratosphere may easily be colder in the troposphere if the tropopause height is lower at night. Nor is the 'difference' technique of extrapolating upward those soundings which terminated at lower levels a reliable technique in this case since it would simply mirror the lapse rate of the warmer ascents

which did reach higher levels, whose representativeness we are trying to determine.

It is of course recognised that the reality of the effect should be verified by careful analysis of the eight years of relatively reliable arctic upper-air data which have now accumulated in national archives and which beg to be summarized. We cannot support these apparent effects on any sound statistical basis with the data available. Rather, we present them merely as suggestions based on the remarkable coincidence of very similar effects at several stations, in the event that they really do hint at physical effects which it is not yet possible to assess.

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Meteorological Measurements from a Minimum Satellite Vehicle

S. Fred Singer

Abstract—A satellite lends itself ideally to the worldwide measurement (1) of the Earth's visible albedo (that is, scattered and reflected sun light), (2) of the infrared emission from the Earth and its atmosphere, and (3) of the altitude distribution of ozone. The present paper specifically does not discuss measurements of solar and other extraterrestrial radiations although it is realized that ultimately they may be of major importance.

The satellite problems are first discussed: A polar orbit is to be preferred. It is necessary for the satellite to be at least partly oriented; for certain orbits a simple spin orientation is sufficient. The detector problems for the ozone, infrared, and visible are treated in detail. At the present state of the art considerations of weight, and also storage and telemetering problems speak against the use of television.

It is demonstrated, however, that the resolution attainable with a minimum satellite and simple detectors is adequate for the following applications: (1) a more accurate determination of the global heat balance and the general trophospheric circulation patterns; (2) long-term albedo changes and their relation to climatic changes; (3) synoptic albedo measurements and the tracking of the development and motion of storm centers; (4) gathering of information which can be correlated with the generation of waves superimposed on the general atmospheric circulation, leading therefore to improved long range weather predictions; (5) determination of variations of the vertical ozone distribution, and resulting applications to stratospheric wind systems, upper trophosphere advection and vertical transport phenomena.

Introduction—One of the major handicaps in present-day meteorology is the lack of observations over a large portion of the Earth's surface. In fact, continuous observations are only carried on over less than five per cent of the total surface of the globe. This means that much of the weather occurring, for example, over the oceans is completely missed. It means also that we have only very imperfect ideas about the average cloudiness over the oceans, the amount of precipitation, and other factors which are important in establishing mean conditions for the purpose of the study of climatology, as well as dynamic meteorology. A satellite overcomes these handicaps by being a truly worldwide observatory on a continuous basis. However, it is limited in what it can do. The purpose of the present article is to examine some observations which are technically feasible for the present minimum satellites, and to give an idea of their importance to meteorology. The larger satellites of the future could carry, for example, elaborate infrared detectors, spectrometers, and television cameras in the visible region, as has been suggested by a number of authors and elaborated upon especially by *Wexler* [1954].

We will confine our discussion to what can be observed by a satellite when looking towards the Earth's surface and the atmosphere. It is reasonable to assume that some of the extraterrestrial radiations, for example, the solar ultraviolet which produces the ozone, micrometeors, etc., have some influence on the weather but the connections are at present not yet established. One may have to collect the data first, and then try to establish significant correlations.

We will here examine systematically optical measurements from the satellite, (1) in the visible range, (2) in the infrared, and (3) in the ultraviolet (for obtaining the altitude distribution of ozone). We shall first discuss some problems connected with the satellite itself, its orbit and its orientation, and its instrumentation. We will then take up some of the applications to important meteorological problems.

Satellite Problems

Choice of satellite orbit and associated problems—By far the most useful orbit for a meteorological satellite is a polar or near-polar orbit, that is, one which is inclined at a very steep angle, even 90°, to the equatorial plane of the Earth. This orbit will cover all or at least most of the Earth's surface and can therefore obtain information about the whole globe. The path swept out by a polar orbit is shown in Figure 1. In order to avoid having to set up a very large number of telemetering receiving stations, it would be desirable to store the information within the satellite and release it when

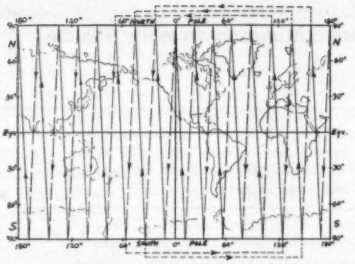

FIG. 1 – Path swept out by a polar orbit satellite (90 minute orbit); here the orbit trace is re-entrant and does not shift over the Earth's surface

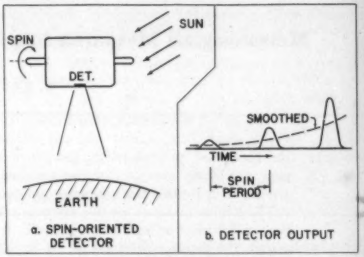

FIG. 2 – Control of space orientation of a satellite by means of spin about a horizontal axis [*Singer*, 1954, 1956]

the satellite transmitter is triggered by the ground receiver. (These, and other technical problems are discussed by *Singer* [1955, 1956].) A most logical choice for the location of ground receivers are the regions in the immediate vicinity of the poles. This means that the information picked up by the satellite must be such that it can be easily compressed and stored. If we were to observe the Earth with a high-resolution television receiver, the storage problems would become quite extensive because of the excellent resolution of the television camera; furthermore we would have a tremendous problem transmitting all of the bits of intelligence within a short period of time. Thus there are several reasons why the initial satellites should carry a much simpler instrumentation; even if we had a light weight television camera available for a satellite, it is doubtful whether full use could be made of its resolution because of the problems of data handling and transmission. Furthermore, a television satellite, as Wexler points out, should be about 4000 mi above sea level where it can take full advantage of its high resolution. We will see that an adequate resolution can be obtained from a minimum satellite just because its orbit is so close to the ground.

Resolution and missed area—In choosing the orbit we must make sure that the orbital pattern traced on the Earth's surface is not reentrant. (A reentrant pattern results when the orbital period is a submultiple of 24 hours. The pattern shown on Fig. 1 is reentrant and is not well chosen.) The most useful altitude would be 300 mi (480 km) which gives an orbital period of 96 min, or a 24-degree rotation of the Earth per orbit. This would give an orbital pattern which interleaves and therefore covers the Earth more efficiently than the 90-minute pattern shown in Figure 1. We want to design our optical instruments so that the amount of missed area is as small as possible and at the same time we want to keep our resolution high. An optimum design might be to have a very high resolution along the line of motion of the satellite and an athwartship coverage so that at latitude 45° the amount of missed area is very close to zero. (Latitude 45° and higher are the regions in which weather systems are generated; the polar front break in the tropopause and the jet stream occur near latitude 55° in the northern summer, and near latitude 35° in the northern winter.) At latitude 45° the distance between satellite traces for a 96-minute orbit is 945 km. This therefore should be the distance subtended on the ground by the instrument in the satellite.

Orientation—The matter of the orientation of the satellite in space is of great importance; in order to perform its observations of the Earth and Earth's atmosphere properly, the detector has to point downward. This would in general require quite an elaborate orientation and control mechanism; for without some definite provisions for orienting the detector, the satellite cannot be used for the meteorological measurements described below. If left to its own devices, the satellite will spin about some axis whose orientation in space is not controlled and not known; this spin-axis may itself undergo an unknown motion in space. The detector readings could then not be interpreted.

A design has been suggested which circumvents the problem of a bulky orientation control mechanism [*Singer*, 1954, 1955]. By giving the satellite a high spin rate along a definitely defined axis, chosen as horizontal, one can get data nearly

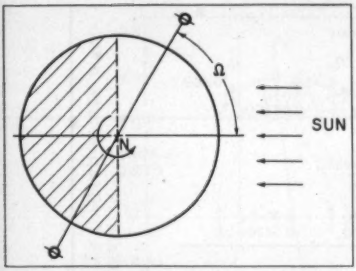

FIG. 3 – Diagram showing orientation of the plane of the satellite orbit (for polar or near-polar orbits) with respect to the Sun-Earth line; to enhance the collection of meteorological data several satellites should be operated simultaneously at different values of Ω

equivalent to those from a completely oriented satellite. The detector (whether a photocell for the visible and ultraviolet, or an infrared bolometer) would be mounted so as to rotate in a plane perpendicular to the spin axis (Fig. 2). Even though it does not view the Earth continuously, it will see it for a fixed fraction of its spin cycle. The detector current can then be smoothed electrically (for example, by a condenser) before being stored and transmitted. The output of the detector is then independent of the spin rate. The instrument should not see the Sun during its spin: the orbital plane could make a large angle with the Sun-Earth line (see Fig. 3) or means can be devised so that the satellite detector does not pick up the Sun; for example, guard photocells surrounding the detector could turn it off during the fraction of the spin cycle when it sweeps past the Sun. It then becomes possible to decrease the angle between the orbital plane and the Sun-Earth line; this is advantageous for many meteorological measurements. A value of Ω of 90°, that is, operation in the twilight plane would be desirable for many other types of observations. It allows, for example, observations of the Sun by means of reasonably omnidirectional instruments, and would allow efficient utilization of solar energy for the production of electrical power to run the satellite instrumentation [*Singer*, 1954, 1955].

SATELLITE INSTRUMENTATION

The desirability of making meteorological observations from satellites is now generally recognized and the measurements suggested here are those which are obviously needed. The main purpose of this section will be to detail the instrumentation problems for the visible and infrared and to develop a new variant of the ozone measurement technique. Applications and examples of the measurements are discussed later.

Albedo of atmosphere and surface—One of the most important measurements from the satellite, and at the same time one of the simplest, is the determination of visible albedo. With a properly oriented satellite (see above) and in a suitable orbit, a simple photocell could give the required measurements. The albedo is mainly due to clouds although certain types of land areas can make large contributions. Albedo values have been obtained by various investigators [see, for example, *Fritz*, 1949, 1951]. Figure 4 shows schematically the albedo situation in the ultraviolet, visible, and the infrared respectively, caused by clouds. Albedo measurements allow one to determine the amount of energy which the Earth and its atmosphere reflect, and therefore is in essence a measurement of the point-by-point energy input to the Earth from the Sun. Albedo measurements thus give the insolation, the input data to the radiation balance calculations which will be discussed later. The Earth's albedo is of importance also in another way: it influences the temperature of the satellite itself. The importance of the effect depends on the reflectivity of the satellite skin, as well as on the orbit parameters, time of year, etc. [*Goldman* and *Singer*, 1957]. This reference also summarizes albedo determinations.

Emission of infrared radiation—In order to complete the radiation data, it is important to get measurements of the infrared radiation leaving the Earth and its atmosphere. Here the well-known analysis by *Simpson* [1928] is very useful. One can conveniently represent the emission from the ground by that of a black body having the surface temperature. Within the atmospheric window (8.5 to 11 μ) this radiation can penetrate the atmosphere and escape into space. There is a slight amount of absorption at 9.6μ by ozone but this does not affect the energy seriously. Below 7μ and above 14μ however, atmospheric absorption, chiefly by water vapor and CO_2, becomes of importance. These gases reradiate at their own temperature, which can be approximated quite closely by a stratosphere temperature of about −60°C. In the intermediate regions, 7 to 8.5 μ and 14 to 11 μ, the absorption varies from 100 to 0 pct (Fig. 5). It is therefore possible to conduct two

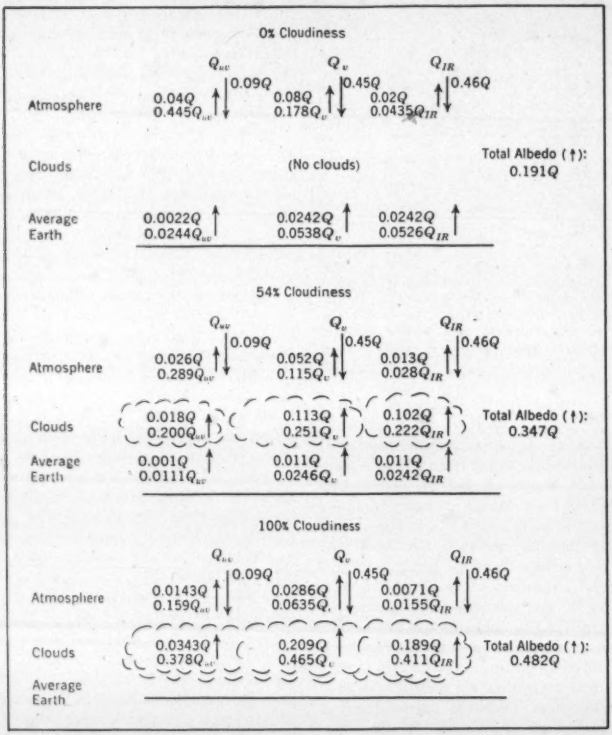

FIG. 4 – Cloud and surface albedo for various degrees of cloudiness (54 pct is the average global cloudiness) [after *Fritz*, 1949; 1951]

types of infrared measurements, (1) with a detector sensitive in the region 8 to 12 μ which would give a measure of the surface temperature, while (2) the other detector covering the whole infrared range from 3 to 30 μ would give a measure also of the stratospheric temperature. A more elaborate infrared instrumentation set-up might measure separately (3) the bands 13–17μ which belong only to CO_2, a regular constituent of the atmosphere; this would give the temperature of a mean of the higher atmosphere, (4) the water vapor rotation bands beyond 17μ would give the "mean" temperature of the top layer of water vapor. If for technical reasons the instrumentation must be limited, then measurement (2) of the total infrared flux leaving the earth would be most valuable for the radiation balance calculations.

We have calculated this infrared flux, using Simpson's method, as a function of the surface temperature. Representative results are shown in Table 1; the radiation to space depends in fact on the vertical distribution of moisture and temperature [*Goldman* and *Singer*, 1957].

Ozone measurements—Aside from direct chemical techniques [*Bowen* and *Regener*, 1951; *Ehmert*, 1952] used in the lower atmosphere, all ozone measurements rely on its optical absorption properties: either (1) in the infrared (at 4.75, 9.6, and 13–15 μ), (2) in the visible, the so-called Chappuis bands, or (3) in the ultraviolet, the

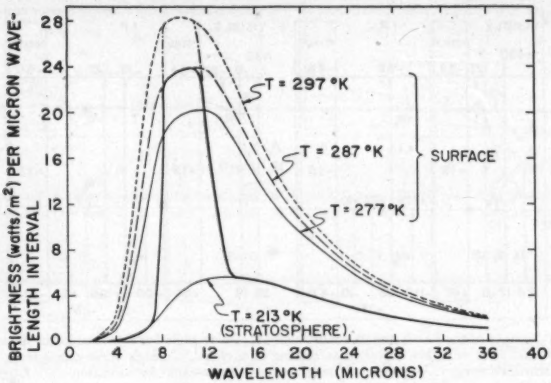

FIG. 5 – Long wave radiation to space showing schematically the contribution of the surface and of the atmosphere (see also Table 1)

Hartley and Huggins bands. The method suggested here and worked out in greater detail [*Singer* and *Wentworth*, 1957] uses the Hartley bands for the measurement of the amount and altitude distribution of ozone. (For the Hartley bands both Lambert's and Beer's laws are obeyed [*Vassy*, 1935; *Strong*, 1941], that is, the absorption coefficients are not pressure-dependent.) This method of ozone determination is based on the classic principle devised by Fabry and Buisson, and refined by *Dobson* [1931]. It is similar to *Götz*' [1934] treatment of the 'inversion effect.'

We need first of all a source of ultraviolet radiation; we can regard the upper atmosphere as an 'ultraviolet mirror' since a large fraction of the ultraviolet is scattered upward from the upper layers of the atmosphere. The picture we have is as follows; solar radiation incident at some zenith angle is attenuated by being scattered and absorbed. For all practical purposes all the scattering is due to the atmospheric molecules and all the absorbing is due to ozone. Because of its extinction the sunlight enters the scattering volume with reduced intensity. The scattering volume is the vertical cone in the atmosphere which the detector in the satellite subtends. A fraction of the light in the scattering volume is scattered upward into the detector but is further reduced in intensity by scattering out and absorption as it now passes vertically through the air and ozone. By suitable choice of wavelengths for the detectors and taking account of the solar zenith angle, it is possible to measure the altitude distribution and concentration of ozone in the upper layers of the Earth's atmosphere [*Singer* and *Wentworth*, 1957]. We have listed in Table 2 the 'effective depths' to which the satellite detector is viewing the atmosphere (defined as the depth below which only ten per cent of the light contribution is made).

TABLE 1 – *Infrared emission as a function of surface temperature, with the top layer of water vapor (of thickness 0.3 mm) at a temperature of −60°C*

Surface temperature, °C	4	14	24
Long wave flux density into space (watts/m²)	175	188	203

TABLE 2 – *Effective depth to which ozone is measured by the satellite detector (as a function of solar zenith angle and of the wave length to which the detector is sensitive); the ozone pressure in cm at NTP is given in brackets; k_a is the absorption coefficient in cm^{-1}*

Wave length	Solar zenith angle		
	0°	30°	60°
3000 *A*, $k_a = 9$	24.5 *km* (0.15)	25 *km* (0.12)	27 *km* (0.08)
2800 *A*, $k_a = 110$	46 *km* (0.01)	47 *km* (0.009)	48 *km* (0.007)

APPLICATIONS

It is of interest to work out some specific applications of the simple observation methods discussed

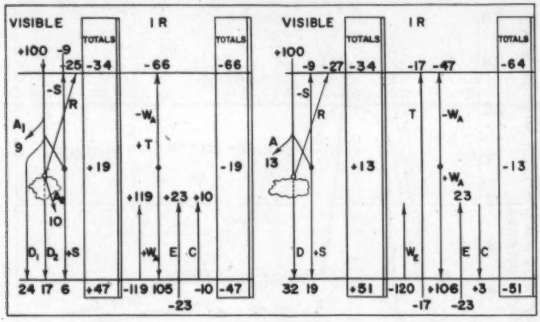

FIG. 6 – Heat balance of the Earth and its atmosphere; A_1, Solar radiation absorbed in the atmosphere and in clouds; R, Reflected solar radiation (depicted as coming from cloud, although some comes from surface); $-S$, Solar radiation scattered upward; $+S$, Solar radiation scattered downward (sky radiation); D_1, Direct solar radiation reaching the Earth; W_E, Emission from the Earth in the absorbing portion of the water-vapor spectrum; $+W_A$, Downward flux of infrared radiation from the atmosphere in the absorbing portion; $-W_A$, Upward flux of infrared radiation from the atmosphere in the absorbing portion; T, Emission from the Earth in the transparent region; E, (Latent) Heat carried to the atmosphere in the hydrologic cycle (evaporation, condensation, precipitation); C, (Sensible) Heat transported downward by eddy currents

above. Most of these applications are to problems which have already been widely discussed among meteorologists. It is useful however to review them from the point of view of satellite observations.

Radiation balance and meridional circulation— Even a cursory examination of current references reveals profound changes over the past few years; comparing, for example, the work of Simpson, Baur, and Phillips on the one hand, and Houghton, Raethjen, Albrecht, and London on the other hand. Some of these differences are due to better measurements of cloud albedo (Neiberger, Fritz, and others). But even today there exist major differences. In Figure 6 we compare the radiation balance as given recently by *Houghton* [1954] and by *Byers* [1954]. The discrepancies are seen to be appreciable. The eddy flux of heat is even in the opposite direction in the two plots. Since it is generally estimated last in order to produce an overall balance, it gives a measure of the discrepancies.

In these determinations the average Earth albedo has to be estimated. *Raethjen* [1950] gives the yearly average as 40 pct, *Houghton* [1954] as 34 pct. Even greater uncertainties exist for the infrared radiation, but especially for the absorption and vertical transport terms. From the viewpoint of the general circulation the most important datum is the radiation balance broken down with latitude. Figure 7 is from *Houghton* [1954] and

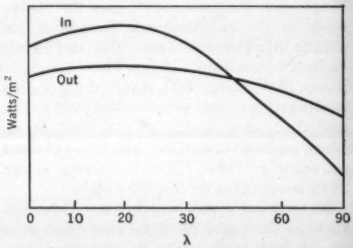

FIG. 7 – Annual mean of solar radiation absorbed by earth and atmosphere (Curve In), and long wave radiation leaving the atmosphere (Curve Out), both plotted vs sine of latitude (so that area under the curve is proportional to energy received or emitted by a latitude zone) [*Houghton*, 1954]

shows the mean annual radiation as a function of latitude. The difference between the incoming short wave energy (solar radiation − albedo) and the radiated long wave energy ($W_A + T$) is most significant, since it determines the driving function for the general circulation which establishes the poleward flow of energy. These two curves are precisely the ones which the satellite can determine for us, not only on a mean annual basis, but over much shorter time intervals. Precise data are of particular necessity for establishing the validity

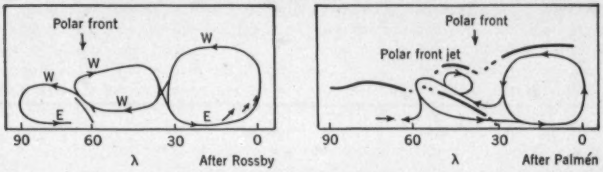

FIG. 8 – Meridional circulation according to *Rossby* [1952] and *Palmén* [1951]; note that Rossby places his polar front much further north and that Palmén's polar 'cell' is not well defined but has large-scale horizontal mixing

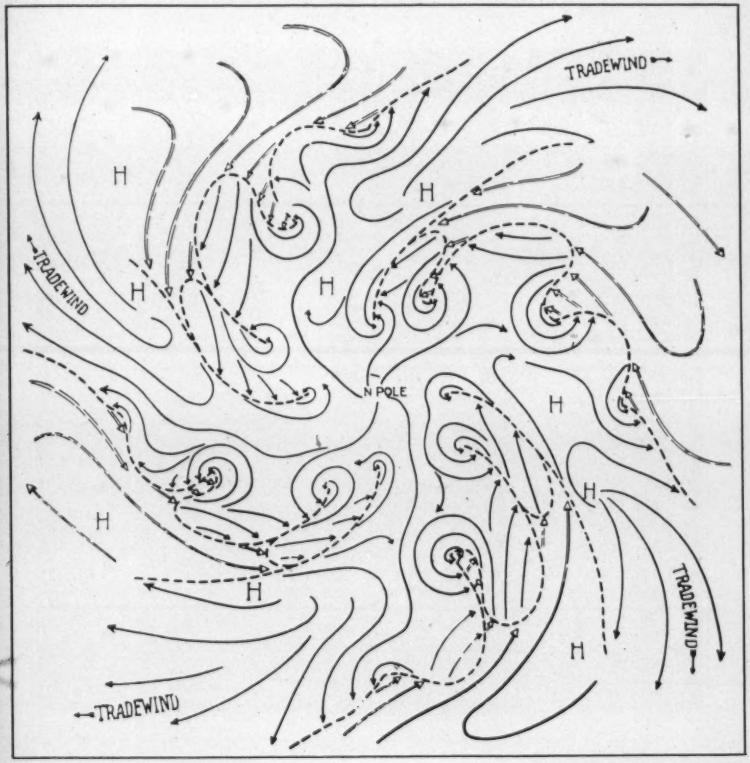

FIG. 9 – Idealized cyclone families [*Bjerknes* and *Solberg*, 1922]; compare this with Fig. 10

of a particular meridional circulation model. As Houghton has pointed out, yearly means have only a limited application to circulation studies. What is really needed are monthly means or even shorter values. It may turn out, and this is speculation, that the tricellular *Rossby* [1952] model works part of the time, but breaks down at other times; then the *Palmén* [1951] circulation scheme would give the more nearly correct picture (Fig. 8). It would be interesting to relate this with the polar front cyclones and the great meanderings of the jet stream.

The satellite data allow us to construct an almost continuous driving function for use in model experiments of the type carried on by Fultz in Chicago and for atmospheric circulation computations of the type carried on at the Princeton Institute, by the US Weather Bureau, and by Rossby. *Phillips* [1956] has had good success in predicting flow patterns by introducing zonal heat input. This points to the possibility of introducing satellite albedo and radiation data directly into machine computations.

Long-term albedo changes and climatic changes—*Brooks* [1951] has carefully analyzed various possible causes for temperature cycles in the Earth's geological history. The possibility exists that climatic changes are due to long-term changes of

FIG. 10 – View of North America (as seen from a 4000-mi high meteorological satellite) constructed by Harry Wexler of the U.S. Weather Bureau; it shows a typical set of cloud patterns: a well-developed cyclonic system over Hudson Bay and extending towards Texas, another cyclone system in the Gulf of Alaska, a hurricane developing in the West Indies, low stratus and fog off lower California coast, Great Lakes, and Newfoundland, and cloud streets in the trade wind region

FIG. 11 – Fig. 10 but with poorer resolution, as seen with photocells from a minimum satellite at 200 – 300 mi

the Earth's albedo produced most likely by an increased cloudiness or increased atmospheric turbidity (due, for example, to volcanic dust). This point of view has been worked out especially by *Wexler* [1953].

It is easy to calculate the dependence of the planetary temperature on the albedo. It is only necessary to assume radiation equilibrium conditions. A simple calculation shows that if the albedo changes from 0.36 by an amount of 0.01, the planetary temperature in turn changes by 1°C.

It is more difficult to calculate the change in the Earth's surface temperature because of the complicated radiation exchange picture between the surface and the atmosphere. *Öpik* [1953] shows that the change in surface temperature is slightly greater.

Synoptic albedo, 'storm patrol'—Since the albedo is largely due to clouds, it provides an excellent means for locating, for example, major cyclonic storm systems. The value of this technique of 'storm patrol' has been discussed by *Wexler* [1954]. He demonstrates that a picture of cloud patterns, obtained by means of a television camera, allows identification of many meteorological features. Unfortunately, incipient storms do not possess such well-pronounced cloud systems. However, since extratropical cyclones usually occur in familes (Fig. 9) leading from northeast to southwest [*Bjerknes* and *Solberg*, 1922], it might be possible to estimate from the fully developed cyclones the probable location of the incipient one.

We want to evaluate here the usefulness of a simple photocell in determining the albedo situa-

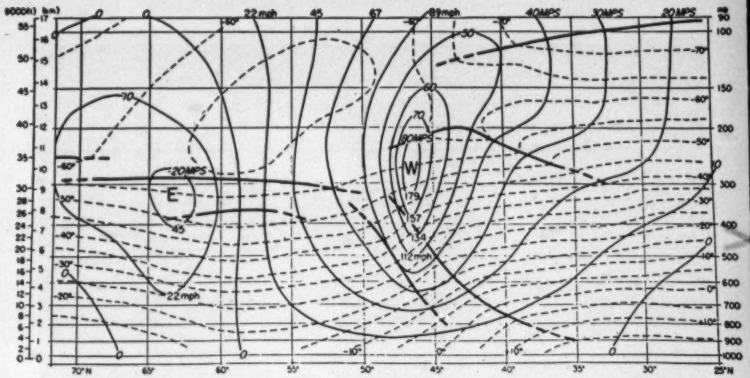

FIG. 12 – Mean cross-section (averaged over several meridians) for 03h00m GMT, Nov. 30, 1946, over North America in a case of approximately straight west-east flow; heavy lines indicate boundaries of the principal frontal layer (polar front) and tropopauses; thin solid lines indicate zonal wind velocity (m/sec), and dashed lines the temperature (°C) [*Palmén*, 1951]

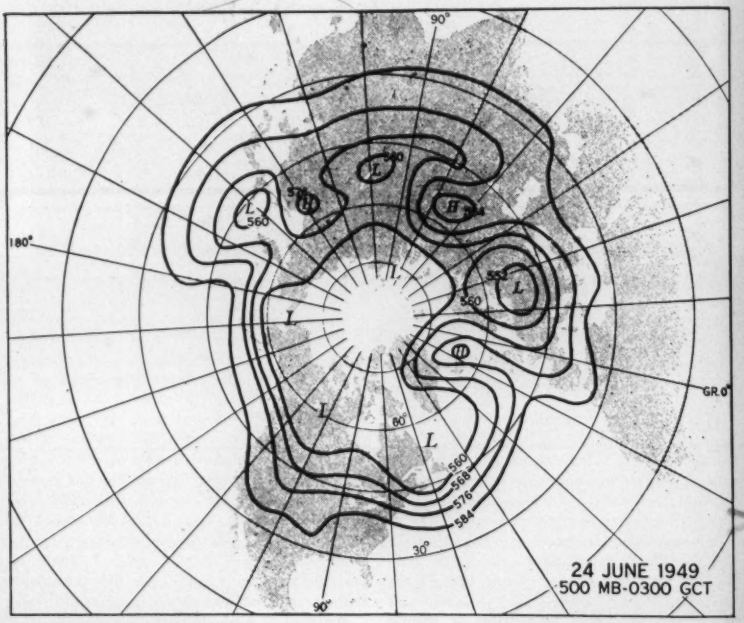

FIG. 13 – A clear-cut example of blocking action in middle latitudes, June 24, 1949; absolute topography of the 500-mb surface is given in decameters [after *Rex*, 1951]

tion. For this purpose we have proceeded as follows: (1) We use as a basis a picture by Wexler of a hypothetical weather situation over the North American continent, with all brightness values carefully reproduced (Fig. 10). The procedure used for constructing the picture has been given by *Wexler* [1954]. (2) We then reconstruct the picture as seen by a photocell from a minimum satellite using a resolution of 400 km (east-west) × 50 km (north-south) (see Fig. 11). The details of the procedure are discussed elsewhere [*Singer*, 1957]. Figure 11 shows adequate resolution for the identification of all important meteorological features; it allows identification of the cyclonic systems, the small hurricane, tradewind clouds, coastline, and snowcover.

Disturbances of the general circulation—While we can visualize directly the application of satellite data to the study of the general circulation, it is more difficult to apply them to the important problem of how, where, and when the major atmospheric disturbances are set off; especially how to predict the amplitude and speed of the long waves superimposed on the zonal circulation which give rise to the extratropical cyclone system and determine the weather, particularly at middle latitudes.

Here we may have to rely on physical guesses and check them by correlations. According to some views [*Rossby*, 1941], disturbances of the general circulation are initiated by surface temperature differences (ocean-land). Here we would rely on satellite measurements of albedo differences between land and oceans, as well as infrared surface temperature measurements (8–12 μ).

On the other hand, the polar-front disturbances can be related to the meanderings of the high latitude jet stream. Namias and others have pointed out that a strong polar jet current may exist and show a strong westerly zonal circulation for some time ('high index' period, one to several weeks), to be followed by a 'low index' period during which large meanderings develop. These perturbations grow into large-amplitude troughs and ridges, and may even lead to complete cutoff of the zonal circulation. At any given time the jet is marked by an intense temperature gradient [*Palmén* and *Nagler*, 1948] as well as by a break in the tropopause. (See Fig. 12; a mean representation, over time, of atmospheric features would average out these important characteristics and show the polar front jet only very weakly.) It is of course extremely important to follow the course

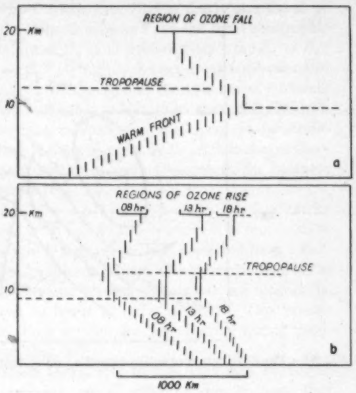

FIG. 14 – Illustrating (a) the fall in ozone content in the case of an advancing warm front, and (b) the rise in the case of an advancing cold front

of the jet stream hourly and globally and to report on its perturbations. A satellite could do this job by observing the position of the south-north temperature gradient in the atmosphere through observations of the infrared radiation flux beyond 12 μ. (It is interesting that a similar method has been proposed to track the meanderings of the Gulf Stream.) The resolution obtained from even a minimum satellite, carrying a simple IR detector, would be quite adequate. A high-index pattern with a strong jet would show a large south-north temperature gradient; a low index pattern, particularly if it leads to blocking (see Fig. 13) would show a temperature gradient from ridge to trough, that is, in the east-west rather than south-north direction.

Rex' [1950, 1951] work indicates that blocking is preferentially initiated at 10° W and 150° W. This lends support to the suggestion that surface features may be responsible also for the generation of low index patterns. Again, satellite observations would make possible a proper study of this most important phenomenon, both in the northern and in the southern hemispheres.

Ozone measurements, stratospheric circulation—The possibility that ozone concentration differences serve to trigger circulation disturbances is generally considered speculative, but may be established or disestablished on the basis of corre-

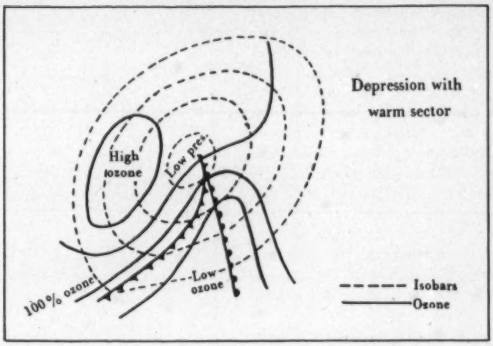

FIG. 15 – The distribution of ozone around a young depression with a very marked warm sector [after *Dobson*, 1930]

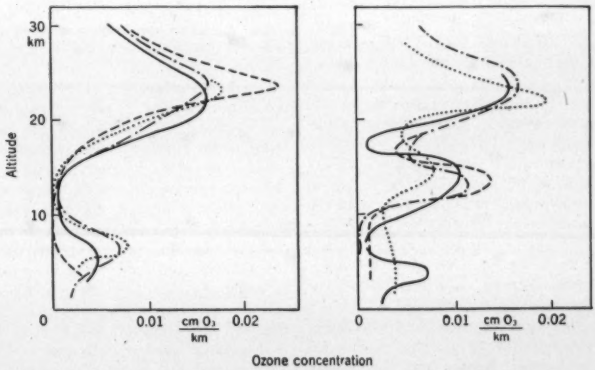

FIG. 16 – Vertical ozone distribution in the spring at Weissenau, Germany, illustrating the production of a secondary ozone maximum by advection: (a) the air between 11 and 16 km was traced as coming from south of 40° N; (b) air between 11 and 16 km from north of 65° N [*Paetzold*, 1955]

lation with worldwide ozone data which the satellite could furnish.

We will rather discuss here the use of ozone as a 'tracer' of atmospheric circulation and the movement of air masses. This feature and techniques for relating it to weather phenomena have been discussed by many authors [*Dobson*, *Brewer*, and *Cwilong*, 1946] (see, for example, Fig. 14, 15 and 16).

From an application of photochemical theory it is possible to explain the ozone distribution above about 40 km. Below this altitude departures from equilibrium are observed [*Paetzold*, 1955] and attributed to atmospheric transport phenomena (Fig. 16). In fact, this is the way in which one can generally explain the presence of ozone in the lower troposphere. (Compare, however, the work of *Frenkiel* [1956].) The major part of the ozone content of the atmosphere is removed from the region of photochemical equilibrium; this can be judged by the absence of a pronounced day-night effect in the ozone content. A thorough discussion of vertical and horizontal flow of ozone has been given by *Paetzold* [1953].

An application of photochemical theory gives the following times required to establish photochemical equilibrium [*Nicolet*, 1954]:

Alt (km)	50	45	40	30	22.5	20
Time	1 hr	Sev hr	1 day	1 mo	1 yr	Sev yr

On this basis one can explain the observed seasonal and latitudinal variation of ozone (Fig. 17).

To account for these observations we may compare them with a theory of stratospheric circulation such as proposed by *Kellogg* and *Schilling* [1951]. These authors use the hydrostatic equation $d\phi/p = -(Mg/RT)\,dz$ to relate the temperature and pressure fields, and an equation of motion in which the horizontal pressure force B_h is balanced by the Coriolis force $2\Omega_z V_\theta$; this relates the slope of the isobaric surfaces θ_p to the zonal geostrophic wind speed V_θ at all latitudes (since $\tan\theta_p = B_h/g^* = 2\Omega_z V_\theta/g^*$; g^* is the apparent acceleration of gravity). But because of the presence of frictional forces and other accelerations there will also be a meridional component of wind speed; in the stratosphere it flows from south to north in the northern winter, and from north to south in the northern summer (Fig. 18).

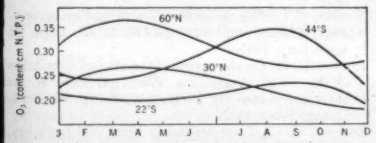

FIG. 17 – Seasonal variation of the atmospheric ozone content at various stations [*Dobson*, 1930]

As pointed out by the authors this flow carries ozone from low latitudes, where it is produced, to the winter pole, where it is protected from breakdown by solar radiation. The spring heating of the polar regions reverses the airflow and returns the ozone to lower latitudes (Fig. 16). This process may then account for the observed spring maximum (Fig. 17).

These ideas, even though they may be largely conjectural, are of great importance since they point out clearly how ozone observations can be related to stratospheric circulation. The ozone observations from the satellite described earlier would cover the 40- to 25-km region, and may therefore be compared with temperature, pressure and wind observations obtainable with the improved radiosondes.

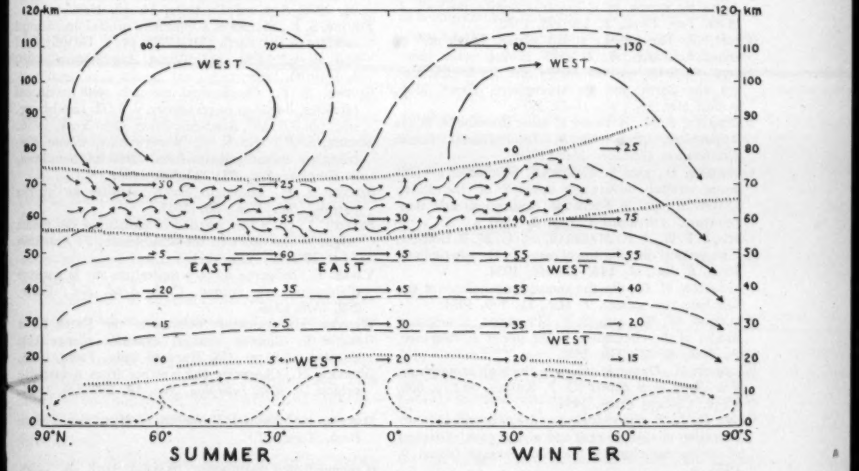

FIG. 18 – Schematic representation of general circulation in meridional cross-section for a northern summer. The heavy vectors represent the mean zonal component of the wind (which are actually normal to the plane), in meters per second. The dashed lines represent the meridional streamlines [from *Kellogg* and *Schilling*, 1951]

Acknowledgments—I am grateful to G. Benton, S. Fritz, J. J. Kelly, and H. Wexler for some very fruitful discussions of various meteorological problems. I am especially indebted to Wexler for permitting the use of his picture (Fig. 10). I would like to thank also M. Galli, D. Goldman, and R. Wentworth, all of the University of Maryland, for assistance in various calculations.

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The Method of Wave Derivatives

JOHN C. FREEMAN, JR. AND LEDOLPH BAER

Abstract—Workers on the water-level problem have been hampered by the lack of a method of computing two-dimensional time-dependent flow of water. The equations of two-dimensional time-dependent flow of an incompressible fluid with a free surface are reformulated in this paper. This formulation, made up of linear combinations of the equations of motion and continuity, results in relations similar to the following

$$D_1A_1/dt + D_2A_2/dt = 0$$

where $D_1/dt = \partial/\partial t + (u + c)\partial/\partial x + (v + c)\partial/\partial y$ and $A_1 = u + v + c$. Similar relationships for non-homogeneous equations are described.

It is demonstrated that $D_1A_1/dt + D_2A_2/dt = 0$ means that the value of A_1 from one point plus the value of A_2 at another point at time t is the same as $A_1 + A_2$ at still another point at time $t + dt$. A computing method, based on motion, addition, and subtraction of isopleths of quantities similar to A_1, is described. A name, 'the method of wave derivatives,' is suggested for this method, and it is applied to the motion of a mound of water in a flat-bottom sea.

Introduction—Since two-dimensional time-dependent problems are now done on electronic computing machines, one might ask the reason for introducing a new graphical method of solution. Although no one can deny that a good knowledge of the physics of a problem is necessary to put it on a computing machine, there is some doubt that the electronic computation is an efficient way of adding to that physical knowledge. The method of wave derivatives is presented as a computing method which describes the physical parameters in the problem and allows for description at the same time that the computation is being performed. The method of characteristics [*Freeman*, 1951] gives similar physical descriptions in problems with only two independent variables.

In order to fix the ideas to be presented in this paper, the problem of water levels is considered. However, the method of wave derivatives applies equally well to any problem in which the equations take the same form, for example, flow under an inversion and flow of a compressible fluid.

The method of wave derivatives as outlined here uses the addition and subtraction of patterns of isopleths. This process should have an immediate appeal for meteorologists, since it is similar to the synoptic analyst's 'thickness' computation. This much of the method of wave derivatives is similar to *Fjørtoft's* [1952] method of numerical weather prediction.

The rest of this paper is confined to the water-level problem as an example. A paper is in preparation applying the same ideas to flow under an inversion. The mathematical development of the general equation which allows the same or a similar treatment is left for a later date or to some group more inclined to abstract discussion.

Discussion—In order to attain the generality of initial and boundary conditions and yet maintain mathematical tractability, it is convenient to restrict the physical generality of the water level problem. It is assumed that the transport of water in a unit column from the surface to the bottom is given by the components uh and vh where h is the total water depth. With this approximation, and the assumption that u and v are the components of the velocity of the water, we can write the equations of continuity and motion of water under the action of wind on a rotating Earth as follows

$$\partial u/\partial t + u\,\partial u/\partial x + v\,\partial u/\partial y + c\,\partial 2c/\partial x = fv + \tau_x/\rho h \quad (1)$$

$$\partial v/\partial t + u\,\partial v/\partial x + v\,\partial v/\partial y + c\,\partial 2c/\partial y = -fu + \tau_y/\rho h \quad (2)$$

$$\partial 2c/\partial t + u\,\partial 2c/\partial x + v\,\partial 2c/\partial y + c\,\partial u/\partial x + c\,\partial v/\partial y = 0 \quad (3)$$

(Eq. (1) and (2) were derived by integration from the bottom to the surface of Eq. (1), p. 576, *Lamb* [1932].) In these equations, $c = \sqrt{gh}$, where g is the acceleration of gravity and h is the height of water above a level bottom; f is the Coriolis parameter; τ_x and τ_y are the components of the wind stress; x and y are arbitrary Cartesian coordinates; and t is the time. In order to develop our computing method, we combine (1) through (3) in various

ways to get new equations as follows

$$[1] + [2] + [3] = fv - fu + \tau_x/\rho h + \tau_y/\rho h$$
$$[1] - [2] + [3] = fv + fu + \tau_x/\rho h - \tau_y/\rho h$$
$$[1] + [2] - [3] = fv - fu + \tau_x/\rho h + \tau_y/\rho h$$
$$[1] - [2] - [3] = fv + fu + \tau_x/\rho h - \tau_y/\rho h$$

(The symbols [1], [2], [3], etc., in the equations stand for the lefthand side of (1), (2), (3), etc., respectively.) To both sides of these equations, we add or subtract

$$c(\partial v/\partial x + \partial u/\partial y)$$

to obtain

$$\partial(u + v + 2c)/\partial t + (u + c)\,\partial(u + v + 2c)/\partial x + (v + c)\,\partial(u + v + 2c)/\partial y = c(\partial v/\partial x + \partial u/\partial y) + fv - fu + \tau_x/\rho h + \tau_y/\rho h \quad (4)$$

$$\partial(u - v + 2c)/\partial t + (u + c)\,\partial(u - v + 2c)/\partial x + (v - c)\,\partial(u - v + 2c)/\partial y = -c(\partial v/\partial x + \partial u/\partial y) + fv + fu + \tau_x/\rho h - \tau_y/\rho h \quad (5)$$

$$\partial(u + v - 2c)/\partial t + (u - c)\,\partial(u + v - 2c)/\partial x + (v - c)\,\partial(u + v - 2c)/\partial y = -c(\partial v/\partial x + \partial u/\partial y) + fv - fu + \tau_x/\rho h + \tau_y/\rho h \quad (6)$$

$$\partial(u - v - 2c)/\partial t + (u - c)\,\partial(u - v - 2c)/\partial x + (v + c)\,\partial(u - v - 2c)/\partial y = c(\partial v/\partial x + \partial u/\partial y) + fv + fu + \tau_x/\rho h - \tau_y/\rho h \quad (7)$$

To simplify these equations, we define the following operators and name them 'wave derivatives'

$$D_1/dt = \partial/\partial t + (u + c)\partial/\partial x + (v + c)\partial/\partial y$$
$$D_2/dt = \partial/\partial t + (u + c)\partial/\partial x + (v - c)\partial/\partial y$$
$$D_3/dt = \partial/\partial t + (u - c)\partial/\partial x + (v - c)\partial/\partial y$$
$$D_4/dt = \partial/\partial t + (u - c)\partial/\partial x + (v + c)\partial/\partial y$$

In addition, we define

$$A_1 = u + v + 2c$$
$$A_2 = u - v + 2c$$
$$A_3 = u + v - 2c$$
$$A_4 = u - v - 2c$$

Now, by adding and subtracting (4) through (7), we eliminate all derivatives other than wave derivatives and substitute in the equations the quantities defined above. One way to do this and to obtain the necessary number of equations is given below.

$$[4] + [5] = D_1A_1/dt + D_2A_2/dt = 2fv + 2\tau_x/\rho h \quad (8)$$

$$[6] + [7] = D_3A_3/dt + D_4A_4/dt = 2fv + 2\tau_x/\rho h \quad (9)$$

$$[4] + [6] = D_1A_1/dt + D_3A_3/dt = 2fv - 2fu + 2\tau_x/\rho h + 2\tau_y/\rho h \quad (10)$$

$$[5] + [7] = D_2A_2/dt + D_4A_4/dt = 2fv + 2fu + 2\tau_x/\rho h - 2\tau_y/\rho h \quad (11)$$

In order to develop our computing method, it is necessary to study the equivalent homogeneous equations in three independent variables. With this in mind, we assume temporarily that $f = 0$, $\tau_x = 0$, $\tau_y = 0$. Eq. (8) through (11) then become

$$D_1A_1/dt + D_2A_2/dt = 0 \quad (12)$$

$$D_3A_3/dt + D_4A_4/dt = 0 \quad (13)$$

$$D_1A_1/dt + D_3A_3/dt = 0 \quad (14)$$

$$D_2A_2/dt + D_4A_4/dt = 0 \quad (15)$$

Eq. (12) through (15) are combinations of wave derivatives. To bring the wave derivative out of the realm of mathematics, consider

$$D_1A_1/dt = \partial A_1/\partial t + (u + c)\partial A_1/\partial x + (v + c)\partial A_1/\partial y \quad (16)$$

This is very similar to the material derivative; in fact, it is a measure of the change in A_1 as we move along a vector $\mathbf{V}_1$ with x component $(u + c)$ and y component $(v + c)$ (Fig. 1). We move in the x direction with the fluid velocity u plus the wave velocity c, and in the y direction with the fluid velocity v plus the wave velocity c. This is the origin of the name, 'wave derivative.' The equation

$$D_1A_1/dt + D_2A_2/dt = 0 \quad (17)$$

has a 'physical' meaning. If we move along the vector $\mathbf{V}_1$ and measure A_1, and along the vector $\mathbf{V}_2$ and measure A_2, the sum of the changes in A_1 and A_2 measured in this way does not change. Two graphical presentations of this idea are given in Figure 2. This figure emphasizes that (12) can

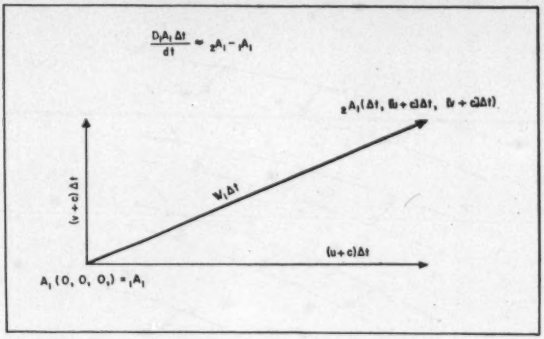

FIG. 1 – The wave derivative, or the change of the quantity A_1 (in time) at a position moving with the vector V

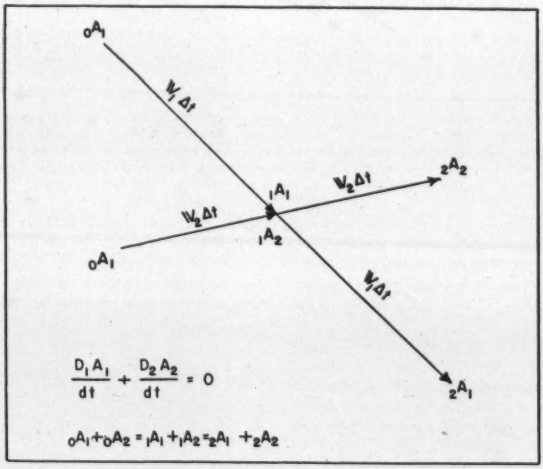

FIG. 2 – The sum of two wave derivatives as it relates the values of two quantities in the vicinity of a point

be interpreted as changes moving either into or out of a point.

The wave derivative is particularly useful in studying fields such as are illustrated in Figure 3. Note that if we have a field of A_1 and A_2, it is easy enough to draw a field of $A_1 + A_2$. If we move the field A_1 with the vector field $\mathbf{V}_1\Delta t$, and move the field A_2 with the vector field $\mathbf{V}_2\Delta t$, then the field $A_1 + A_2$ can be drawn by the intersection of these moved A_1 and A_2 fields. This process and a proof that the fields can be obtained in this way are illustrated in Figure 3.

If we move the solid lines in Figure 3 with the indicated vectors, the dashed lines will result. The intersections marked ① now are at the points marked ②. Eq. (17) shows that this is true. The way the dashed lines were drawn assures us that we moved to the point ② with a vector $\mathbf{V}_1$ from a

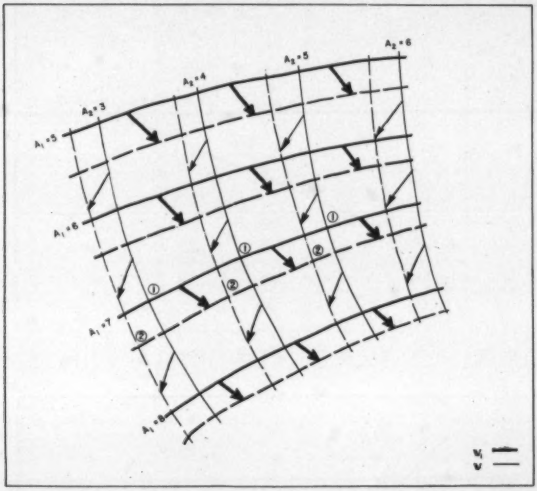

FIG. 3 – The wave derivative applied to two fields; lines of constant A_1 (heavy lines) are moved at velocity $\mathbf{V}_1$ (x,y) (heavy arrows); lines of constant A_2 (light lines) are moved for the same time with velocities $\mathbf{V}_2$ (x,y) (light arrows); the values of $A_1 + A_2$ at the intersection of A_1 and A_2 lines at the initial time (solid lines) are the same as the values of $A_1 + A_2$ at the intersection of the moved A_1 and A_2 lines at the final time (dashed lines)

line with the value $A_1 = 7$, say. We are also assured that we moved into ② along $\mathbf{V}_2$ from a point along which $A_2 = 5$, say. But these two lines intersect at the point ①. Thus, we have moved the constant value of $A_1 + A_2 = 12$ from the point ① to the point ②.

The analysis above indicates that (8) through (11) are easier to solve graphically when f and τ can be neglected. If they cannot be neglected, it is obvious that a similar system of computing would be convenient. A similar computing system results if we incorporate the terms similar to $2(fv + \tau_x/\rho h)$ in the wave derivatives. Consider (8); we multiply and divide by $\partial A_1/\partial x$ to get

$$D_1 A_1/dt + D_2 A_2/dt = \left[2\left(fv + \frac{\tau_x}{\rho h}\right) \Big/ \frac{\partial A_1}{\partial x}\right] \partial A_1/\partial x$$

Then we define the following operators

$$D_1'/dt = \partial/\partial t + \left[(u + c) - 2\left(fv + \frac{\tau_x}{\rho h}\right) \Big/ \frac{\partial A_1}{\partial x}\right] \partial/\partial x + (v + c)\partial/\partial y.$$

Eq. (8) can then be written $D_1'A_1/dt + D_2A_2/dt = 0$. This equation can be treated just like (17) except that the vector $\mathbf{V}_1'$ involves $\partial A_1/\partial x$. The set of operators we use for the complete set of (8) through (11) are the previous set plus

$$D_1'/dt = \partial/\partial t + \left[(u + c) - \left(2fv + 2\frac{\tau_x}{\rho h}\right) \Big/ \frac{\partial A_1}{\partial x}\right] \partial/\partial x + (v + c)\partial/\partial y$$

$$D_4'/dt = \partial/\partial t + \left[(u - c) - \left(2fv + 2\frac{\tau_x}{\rho h}\right) \Big/ \frac{\partial A_4}{\partial x}\right] \partial/\partial x + (v + c)\partial/\partial y$$

$$D_1''/dt = \partial/\partial t + \left[(u + c) - \left(2fv + \frac{\tau_x}{\rho h}\right) \Big/ \frac{\partial A_1}{\partial x} - \left(-2fu + \frac{\tau_y}{\rho h}\right) \Big/ \frac{\partial A_1}{\partial x}\right] \partial/\partial x + (v + c)\partial/\partial y$$

$$D_4''/dt = \partial/\partial t + \left[(u-c) - \left(2fv + 2\frac{\tau_x}{\rho h}\right)\Big/\frac{\partial A_4}{\partial x} + \left(-2fu + 2\frac{\tau_y}{\rho h}\right)\Big/\frac{\partial A_4}{\partial x}\right]\partial/\partial x + (v+c)\partial/\partial y$$

Using these definitions, we obtain the following formulation of (8) through (11)

$$D_1'A_1/dt + D_2A_2/dt = 0 \quad (18)$$

$$D_2A_3/dt + D_4'A_4/dt = 0 \quad (19)$$

$$D_1''A_1/dt + D_2A_3/dt = 0 \quad (20)$$

$$D_2A_2/dt + D_4''A_4/dt = 0 \quad (21)$$

The different method of finding $\mathbf{V}_1'$, $\mathbf{V}_4'$, $\mathbf{V}_1''$, $\mathbf{V}_4''$ is all that distinguishes this method from that used in solving (12) through (14).

Note that, given u, v, and c for one time, we can find A_1, A_2, A_3, and A_4 for that time. We can then use the equations above to find $A_1 + A_2$, $A_3 + A_4$, $A_1 + A_3$, $A_2 + A_4$ for a later time. Now, however, complications arise. Given the set of equations

$$A_1 + A_2 = K_1$$
$$A_3 + A_4 = K_2$$
$$A_1 + A_3 = K_3$$
$$A_2 + A_4 = K_4$$

we cannot find A_1, A_2, A_3, and A_4 directly, because the equations are not linearly independent. This can be seen most easily by adding the first equations and the last two equations; the same equation results. However, we are seeking only the three unknowns, u, v, and c. From the definitions of the A_i we see that

$$A_1 + A_2 = 2(u + 2c)$$
$$A_3 + A_4 = 2(u - 2c)$$
$$A_1 + A_3 = 2(u + v)$$
$$A_2 + A_4 = 2(u - v)$$

We use these relationships to find

$$u = \frac{(A_1 + A_3) + (A_2 + A_4)}{4} \quad (22)$$

$$v = \frac{(A_1 + A_3) - (A_2 + A_4)}{4} \quad (23)$$

$$2c = \frac{(A_1 + A_2) - (A_3 + A_4)}{4} \quad (24)$$

From these relationships we find

$$A_1 = \frac{(A_1 + A_3)}{2} + \frac{(A_1 + A_2) - (A_3 + A_4)}{4} \quad (25)$$

$$A_2 = \frac{(A_2 + A_4)}{2} + \frac{(A_1 + A_2) - (A_3 + A_4)}{4} \quad (26)$$

$$A_3 = \frac{(A_1 + A_3)}{2} - \frac{(A_1 + A_2) - (A_3 + A_4)}{4} \quad (27)$$

$$A_4 = \frac{(A_2 + A_4)}{2} - \frac{(A_1 + A_2) - (A_3 + A_4)}{4} \quad (28)$$

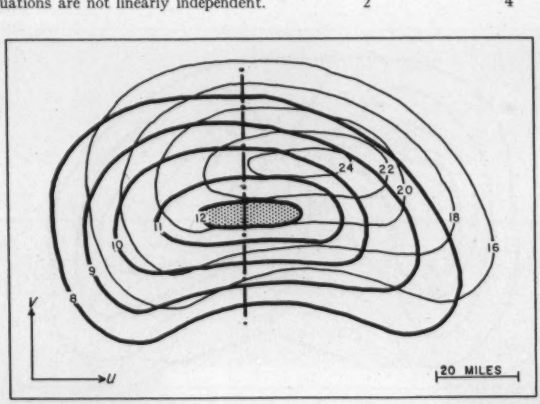

FIG. 4 – The heavy lines show the initial distribution of c with values expressed in knots; the value 8 knots exists all over the area outside the closed 8-knot line; the light lines are the moved values of A_1 or ${}_1B_1$, at the time $A_1 = 2c$; the maximum isopleth of c is shaded as a locator

Once the various terms of the form $(A_1 + A_2)$ are found, we can compute all other needed quantities by graphical addition and subtraction. We find $2c$ first and then a single addition is required to find each A_i.

An example is given here, in which the stress and the Coriolis parameter are neglected in the problem. The results are also compared with one-dimensional computations for a roughly similar situation to show that the behavior illustrated is not entirely unexpected.

Example—The method of wave derivatives applied to a mound of water with $f = \tau_x = \tau_y = 0$.

In this example a large basin with a smooth level bottom where the depth of the water is described by the values of $c = \sqrt{gh}$ is assumed. This particular case is illustrated by the heavy lines in Figure 4 which show at time $t = 0$ a mound of water surrounded by water of a constant depth. The shape is arbitrary and was designed to be as general as possible. The problem is to show time changes graphically.

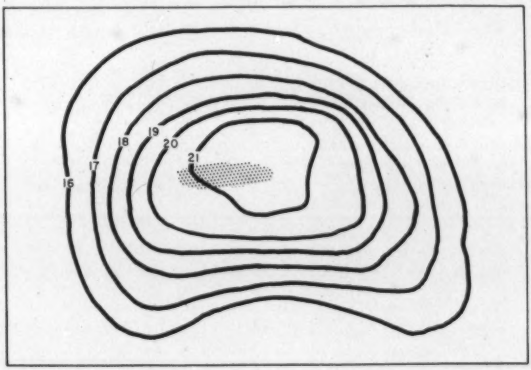

FIG. 5 – After the first hour, this is the distribution of $(A_1 + A_2)/2$, that is, $({}_1A_1 + {}_1A_2)/2$

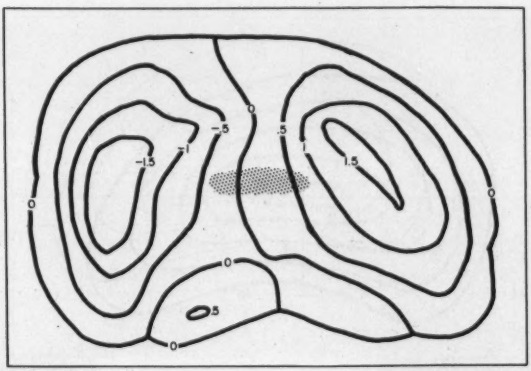

FIG. 6 – Distribution of u after one hour, that is, ${}_1u$; note that it reaches a maximum in the region of maximum pressure gradient in the x direction

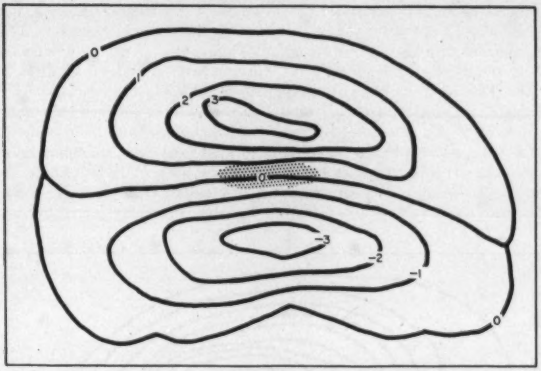

FIG. 7 – Distribution of ${}_1v$; the two cells have formed with maximum velocities in the region of maximum initial pressure gradient in the x direction

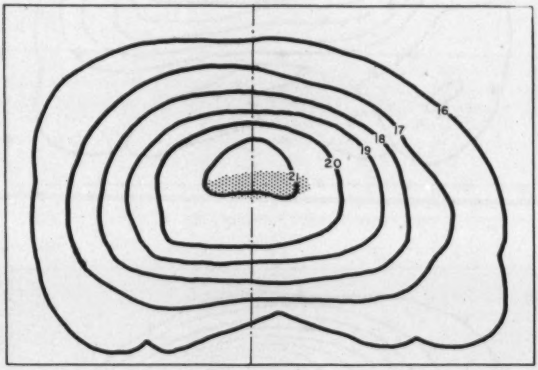

FIG. 8 – Distribution of $2\ {}_1c$; the area of $2c > 16$ knots has greatly enlarged

The first step is the easiest since, initially, ${}_0u = {}_0v = 0$, and ${}_0A_1 = {}_0A_2 = -{}_0A_3 = -{}_0A_4 = 2\ {}_0c$ (minor subscripts refer to time). The light lines in Figure 4 show

$$ {}_0A_1 + \frac{D_1 A_1}{dt}\bigg|_0 $$

after one hour, which we define as ${}_1B_1$. Not illustrated, but necessary, are ${}_1B_2$, ${}_1B_3$, and ${}_1B_4$, which are computed similarly to the one illustrated. Figure 4 shows for a field what Figure 1 showed for a single point, if it is remembered that ${}_0A_1 = 2\ {}_0c$. The moving of A_1, A_2, A_3, and A_4 is the slowest and most tedious step of the entire method.

The next step requires adding and subtracting the new ${}_1A_1$, ${}_1A_2$, ${}_1A_3$, and ${}_1A_4$ fields in accordance with (12) through (15). This is the step explained by Figure 3. Figure 5 shows $({}_1A_1 + {}_1A_2)$. A similar computation gives $({}_1A_2 + {}_1A_4)$, $({}_1A_3 + {}_1A_4)$, and $({}_1A_1 + {}_1A_3)$. Now, using (22) and (23), Figures 6 and 7 were prepared showing the ${}_1u$ and ${}_1v$ built up during the first time interval. Following (24) and (25), $2\ {}_1c$ and ${}_1A_1$ were drawn as shown in Figures

8 and 9. Not illustrated but also needed are ${}_1A_2$, ${}_1A_3$, ${}_1A_4$. This completes the first time step.

Step 2 is encumbered with the various factors $({}_1u + {}_1c)$, $({}_1u - {}_1c)$, $({}_1v + {}_1c)$, and $({}_1v - {}_1c)$ as described by (16). This seems to be most easily handled by preparing separate charts for each factor. Each field, ${}_1A_1$, ${}_1A_2$, ${}_1A_3$, and ${}_1A_4$, can then be moved as before from only two charts. A two-hour movement of ${}_1A_1$ is illustrated in Figure 10, and the sum, $({}_2A_1 + {}_2A_2)$, is illustrated in Figure 11. The two-hour unit more strongly indicates the changes occurring. Finally, ${}_2u$, ${}_2v$, and ${}_2c$ are shown in Figures 12, 13, and 14.

Figure 14 is of special interest, since it shows that, where the water was originally in a single mound, it has split into two centers. Some 'feeling' for this effect is obtained from the various steps. Notice also in Figure 10 that the lines of ${}_2B_1$ are crowded together in the upper right. This might elad to a 'jump' in the near future.

The cusped shape of the outer boundary of the diagrams is probably caused by the absence of a

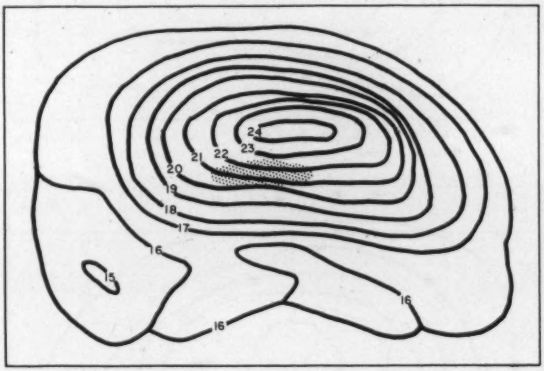

FIG. 9 – The distribution of ${}_1A_1$; note that it is similar to $2\ {}_1c_1$ except near the bottom left where large values of ${}_1u$ and ${}_1v$ are near small values of ${}_1c_1$

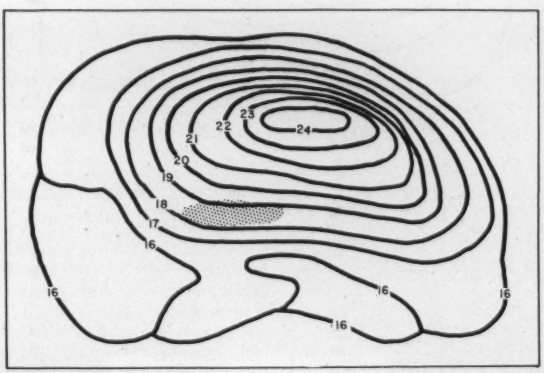

FIG. 10 – The moved values of A_1 from t = one hour to t = three hours, that is, ${}_2B_1$

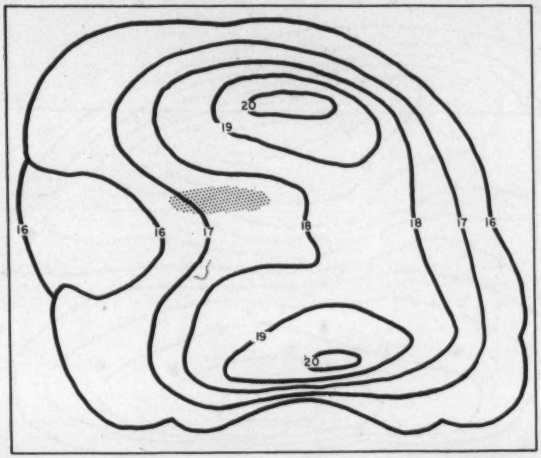

FIG. 11 – The distribution of $({}_2A_1 + {}_2A_2)/2$; this is the first indication of the splitting of the mound of water

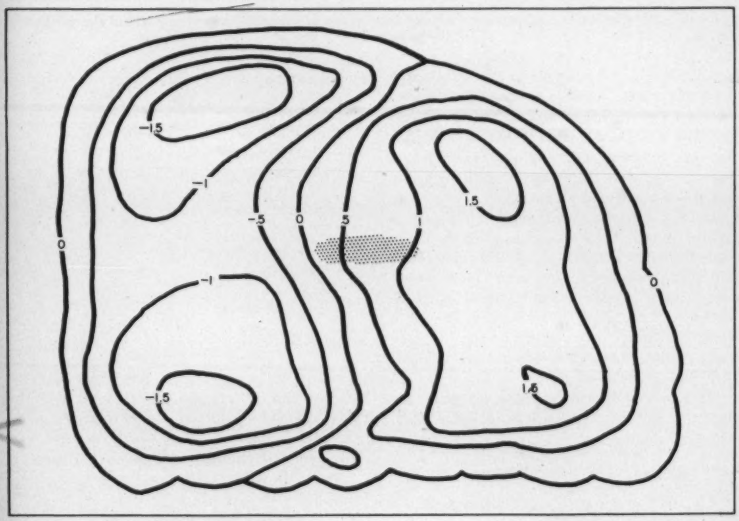

FIG. 12 – Distribution of ${}_1u$; even this velocity field is splitting

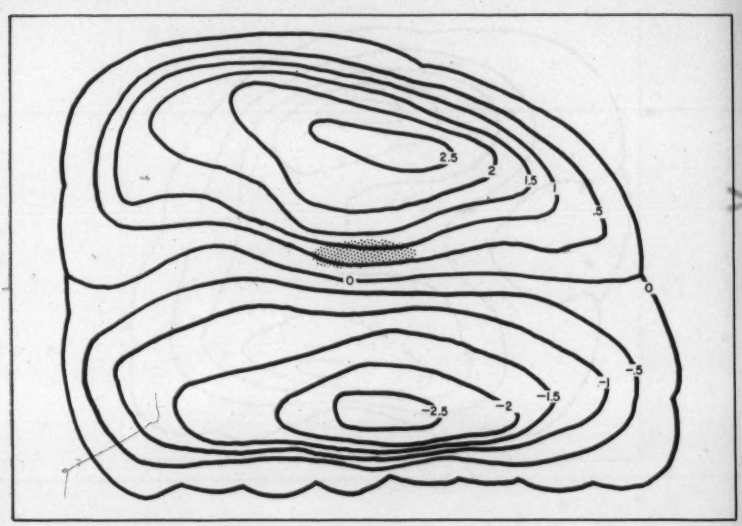

FIG. 13 – Distribution of $_{3}w$; this cellular velocity distribution is the only obvious early hint of the splitting of the mound of water

gradual sloping of the mound into the level water. Thus the outer boundary is actually (in this example) a jump. The finite-sized time increments probably accentuate this effect. Remembering the fact that the outer isopleths of many of the figures coincide, and that the other (inner) isopleths do not, makes much of the work easier.

The characteristics diagram shown in Figure 15 has the same initial distribution of c as is shown along the center line of Figure 4. The same center line is also shown in Figures 8 and 14. For comparison, a few values of c from Figure 14 have been placed on the characteristics diagram (Fig. 15). When the effects of curvature are qualitatively considered, the one- and two-dimensional computations agree reasonably well.

In summary, the charts drawn for each time step used in the wave derivative computation were the following

Initial distribution

(1) c
(2) u
(3) v

allowing preparation of

(4) A_1, since $A_1 = u + v + 2c$
(5) A_2, since $A_2 = u - v + 2c$
(6) A_3, since $A_3 = u + v - 2c$
(7) A_4, since $A_4 = u - v - 2c$

and the vector component fields

(8) $u + c$
(9) $u - c$
(10) $v + c$
(11) $v - c$

then moving

(12) A_1 with $(u + c)$ and $(v + c)$ to get B_1
(13) A_2 with $(u + c)$ and $(v - c)$ to get B_2
(14) A_3 with $(u - c)$ and $(v - c)$ to get B_3
(15) A_4 with $(u - c)$ and $(v + c)$ to get B_4
(16) graphical addition of B_1 and B_2 gives $_1A_1 + {}_1A_2$
(17) B_3 and B_4 give $_1A_3 + {}_1A_4$
(18) B_1 and B_3 give $_1A_1 + {}_1A_3$
(19) B_2 and B_4 give $_1A_2 + {}_1A_4$

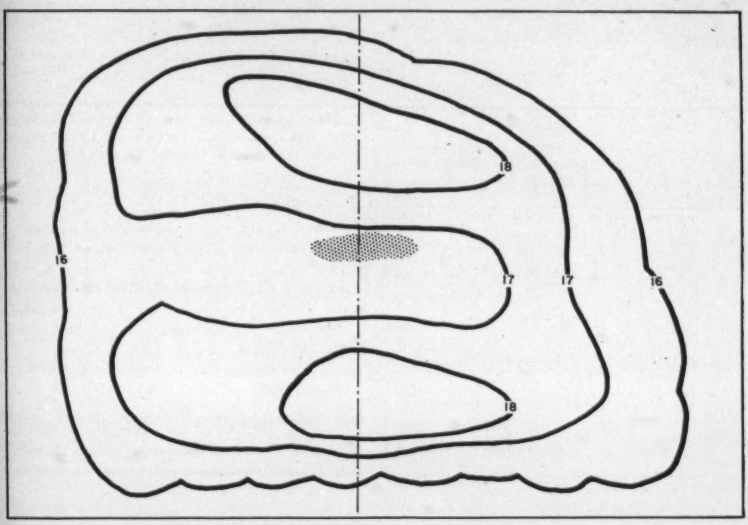

FIG. 14 – Distribution of 2 $_{2}c$; we now have two mounds of water moving in opposite directions; our oval-shaped distribution has shown some of the properties of a radially symmetric flow and some of those of a one-dimensional flow; the U-shape of the 2 $_{2}c$ = 17 line is similar to axially symmetric flow; the two 2 $_{2}c$ = 18 lines are manifestations of one-dimensional properties

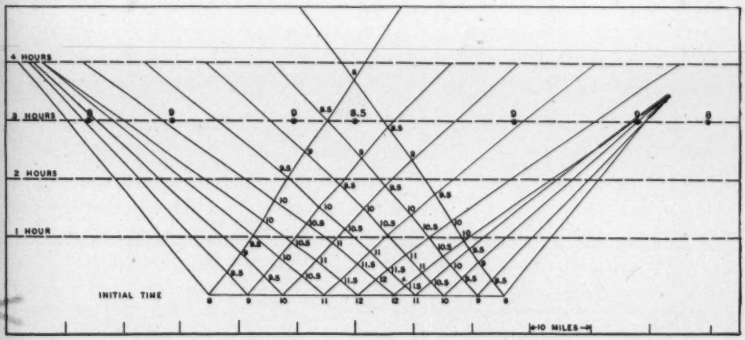

FIG. 15 – A one-dimensional computation with initial conditions similar to those along a cross section of our mound of water; the numbers by the heavy dots at t = 3 hours are values from Figure 14; these should be compared with the value on the nearest characteristic

further

$$(20)\quad \frac{({}_1A_1 + {}_1A_3) + ({}_1A_2 + {}_1A_4)}{4} = {}_1u$$

$$(21)\quad \frac{({}_1A_1 + {}_1A_3) - ({}_1A_2 + {}_1A_4)}{4} = {}_1v$$

$$(22)\quad \frac{({}_1A_1 + {}_1A_2) - ({}_1A_3 + {}_1A_4)}{8} = {}_1c$$

Now, the next step can begin, either by returning to step 4, or, more easily, by introducing the following additional steps

$$(23)\quad {}_1A_1 = \frac{({}_1A_1 + {}_1A_3)}{2} + \frac{({}_1A_1 + {}_1A_2) - ({}_1A_3 + {}_1A_4)}{4}$$

$$(24)\quad {}_1A_2 = \frac{({}_1A_2 + {}_1A_4)}{2} + \frac{({}_1A_1 + {}_1A_2) - ({}_1A_3 + {}_1A_4)}{4}$$

$$(25)\quad {}_1A_3 = \frac{({}_1A_1 + {}_1A_3)}{2} - \frac{({}_1A_1 + {}_1A_2) - ({}_1A_3 + {}_1A_4)}{4}$$

$$(26)\quad {}_1A_4 = \frac{({}_1A_2 + {}_1A_4)}{2} - \frac{({}_1A_1 + {}_1A_2) - ({}_1A_3 + {}_1A_4)}{4}$$

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Propagation and Dissipation of Long Internal Waves

MAURICE RATTRAY, JR.

Abstract—The effect of friction on the propagation of long internal waves in a rotating ocean is investigated theoretically for the simple case of a two-layer system subjected to a constant eddy viscosity. Waves of inertial period are excluded. Typical distances for a 50-pct decrease in amplitude are found to be 1000 to 2000 km.

List of symbols—The following symbols are used. Primes refer to the upper layer; seconds to the lower layer.

x, y, z	Cartesian coordinates of position, with $z = 0$ at the mean interface level
t	Time
u, v, w	Components of water velocity
ζ	Elevation of upper surface of layer
ζ_0	Value of ζ at time $t = 0$ and position $x = 0$
g	Acceleration due to gravity
ν	Eddy viscosity
ω	Angular velocity of rotation of ocean area
ρ	Density of sea water
$\Delta\rho$	Density difference between two layers
h	Mean layer depth
σ	Frequency of the internal wave
k	Wave number of the internal wave
γ	Damping coefficient of the internal wave
β_1	$\sqrt{(\sigma + 2\omega)/2\nu}$
β_2	$\sqrt{(\sigma - 2\omega)/2\nu}$
ϵ	ζ_0'/ζ_0''
R	$g(\Delta\rho/\rho)(\gamma + ik)^2(h' + h'')/(\sigma^2 - 4\omega^2)$
Θ	$\epsilon/(\Delta\rho/\rho)$
B_1	$\beta_1(h' + h'')$
B_2	$\beta_2(h' + h'')$
p	$\frac{1}{2} - \omega/\sigma$
q	$\frac{1}{2} + \omega/\sigma$
S_0	$-[(h' + h'')^2/h'h'']$
S_1	Real part of $R/S_0 - 1$
T_1	Imaginary part of $R/S_0 - 1$
Φ_0	$-[h''/(h' + h'')]$
Φ_1	Real part of $\Theta/\Phi_0 - 1$
Ψ_1	Imaginary part of $\Theta/\Phi_0 - 1$
P	$p/2B_1$
Q	$q/2B_2$.

Introduction—Evaluation of oceanographic data is at best uncertain where the influence of long internal waves cannot be determined. This is clearly shown by the California Current where an apparent eddy structure is found to be caused by internal oscillations of diurnal period [*Defant*, 1950a]. From the apparent wide distribution of such internal waves it is reasonable to suppose that the possibility of error exists in the interpretation of much similar data. A knowledge of the occurrence and behavior of long internal waves in the ocean thus becomes of prime importance for the advance of oceanography.

Obtaining information on internal waves at sea is a difficult process which requires long series of observations for statistically valid results. It has been demonstrated that reported internal waves, in many cases, may be only harmonic representations of short series of random data [*Haurwitz*, 1952, 1953; *Rudnick* and *Cochrane*, 1951]. In addition, to describe the behavior of the internal waves adequately it is necessary to take measurements simultaneously at three stations [*Haurwitz*, 1953].

The principal reason for the difficulty in obtaining internal-wave data in the ocean is the lack of an adequate theory to guide the investigations. Even the presence of internal tide waves is not well explained. The resonance theory [*Haurwitz*, 1950; *Defant*, 1950b] is inadequate because of the large frictional damping and the narrow belt of resonance for these waves. Since internal waves of tidal period have been found mainly in offshore regions rather than in the open ocean, a mechanism of generation associated with the ocean boundaries is suggested [*Rudnick* and *Cochrane*, 1951]. Model experiments have shown the generation of internal waves by the passage of surface waves over bottom irregularities [*Zeilon*, 1934], but it was felt that this did not offer an explanation for the observed internal tide waves since their amplitudes would be decreased rapidly by friction and divergence. However, internal waves generated by the action of surface tides over the continental shelves will not be subject to radial divergence as from a point source, but will in general undergo convergence on traveling seaward from an outer boundary source. More recently, *Reid* [1956] reports results from simultaneous observations at stations 40, 160, and 320 mi offshore which demonstrate internal tides at the inshore station but not at the other two. He also suggests that the waves found originate near the coast in the action of the surface tides and that, since the length of such waves, if free, is short, they either dissipate before proceeding far offshore, or

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more likely, are so distorted by the varying density structure and water velocity that they are no longer recognized. A more complete literature survey on the creation and propagation of internal waves [*Davis* and *Patterson*, 1956] summarizes our present state of knowledge in this field. It is proposed, therefore, to derive expressions for the effect of friction on internal wave motion for the case of a rotating Earth. Additional mathematical details of this analysis may be found in *Rattray* [1954].

Mathematical formulation—For mathematical simplicity the problem considered is the propagation of long internal waves through a two-layer fluid on a rotating disk, assuming constant eddy viscosity. A right-handed coordinate system is used with the origin at the mean level of the interface; the z-axis vertical, positive upwards; and the x-axis positive in the direction of wave travel. The following assumptions are made: the vertical accelerations are negligible, permitting use of a hydrostatic pressure distribution; all quantities are independent of position in the y direction; the water is incompressible; and u, v, w, and variations in ρ and p are sufficiently small that terms of higher order can be neglected.

The equations of motion then become, for the upper layer

$$\frac{\partial u'}{\partial t} - 2\omega v' - \nu \frac{\partial^2 u'}{\partial z^2} = -g \frac{\partial \zeta'}{\partial x} \tag{1}$$

$$\frac{\partial v'}{\partial t} + 2\omega u' - \nu \frac{\partial^2 v'}{\partial z^2} = 0 \tag{2}$$

and for the lower layer

$$\frac{\partial u''}{\partial t} - 2\omega v'' - \nu \frac{\partial^2 u''}{\partial z^2} = -g \frac{\partial \zeta'}{\partial x} - g \frac{\Delta\rho}{\rho} \frac{\partial \zeta''}{\partial x} \tag{3}$$

$$\frac{\partial v''}{\partial t} + 2\omega u'' - \nu \frac{\partial^2 v''}{\partial z^2} = 0 \tag{4}$$

The equation of continuity is

$$\int_{\zeta''}^{h'+\zeta'} \frac{\partial u'}{\partial x}\, dz = \frac{\partial \zeta''}{\partial t} - \frac{\partial \zeta'}{\partial t} \tag{5}$$

for the upper layer, and

$$\int_{-h''}^{\zeta''} \frac{\partial u''}{\partial x}\, dz = -\frac{\partial \zeta''}{\partial t} \tag{6}$$

for the lower layer.

The boundary conditions are: at the free surface there is no tangential stress, or at $z = h'$

$$\frac{\partial u'}{\partial z} = \frac{\partial v'}{\partial z} = 0 \tag{7}$$

at the interface, the velocities and tangential stresses are continuous, or at $z = 0$

$$u' = u'', \qquad v' = v''$$

$$\frac{\partial u'}{\partial z} = \frac{\partial u''}{\partial z}, \qquad \frac{\partial v'}{\partial z} = \frac{\partial v''}{\partial z} \tag{8}$$

at the bottom there is no slippage, or at $z = -h''$

$$u'' = v'' = 0 \tag{9}$$

Eq. (1)–(9) are solved in a manner similar to that applied to tidal waves on the Siberian shelf by *Sverdrup* [1927].

Solution—A solution is found by assuming

$$\zeta' = \zeta_0' e^{-\gamma z} e^{i(\sigma t - kx)} \tag{10}$$

$$\zeta'' = \zeta_0'' e^{-\gamma z} e^{i(\sigma t - kx)} \tag{11}$$

where ζ_0', ζ_0'', γ, σ, and k are all constants characteristic of the motion. The general solutions of (1)–(4) are then

$$u' = -\frac{ig\zeta_0'(\gamma + ik)e^{-\gamma z}e^{i(\sigma t - kx)}}{\sigma^2 - 4\omega^2} [\sigma + A_1' e^{(1+i)\beta_1 z} + A_2' e^{-(1+i)\beta_1 z} - A_3' e^{(1+i)\beta_2 z} - A_4' e^{-(1+i)\beta_2 z}] \tag{12}$$

$$v' = -\frac{g\zeta_0'(\gamma + ik)e^{-\gamma z}e^{i(\sigma t - kx)}}{\sigma^2 - 4\omega^2} [-2\omega + A_1' e^{(1+i)\beta_1 z} + A_2' e^{-(1+i)\beta_1 z} + A_3' e^{(1+i)\beta_2 z} + A_4' e^{-(1+i)\beta_2 z}] \tag{13}$$

$$u'' = -\frac{ig\left(\zeta_0' + \frac{\Delta\rho}{\rho}\zeta_0''\right)(\gamma + ik)e^{-\gamma z}e^{i(\sigma t - kx)}}{\sigma^2 - 4\omega^2} [\sigma + A_1'' e^{(1+i)\beta_1 z} + A_2'' e^{-(1+i)\beta_1 z} - A_3'' e^{(1+i)\beta_2 z} - A_4'' e^{-(1+i)\beta_2 z}] \tag{14}$$

$$v'' = -\frac{g\left(\zeta_0' + \frac{\Delta\rho}{\rho}\zeta_0'\right)(\gamma + ik)e^{-\gamma z}e^{i(\sigma t - kx)}}{\sigma^2 - 4\omega^2} [-2\omega + A_1'' e^{(1+i)\beta_1 z} + A_2'' e^{-(1+i)\beta_1 z} + A_3'' e^{(1+i)\beta_2 z} + A_4'' e^{-(1+i)\beta_2 z}] \tag{15}$$

The constant coefficients A are given by

$$\frac{2\epsilon}{\sigma - 2\omega}[e^{-2(1+i)\beta_1 h''} + e^{2(1+i)\beta_1 h'}]A_1' = \frac{1}{2}\frac{\Delta\rho}{\rho}[1 + e^{-2(1+i)\beta_1 h''}] - \left(\epsilon + \frac{\Delta\rho}{\rho}\right)e^{-(1+i)\beta_1 h''} \tag{16}$$

$$\frac{2\left(\epsilon+\frac{\Delta\rho}{\rho}\right)}{\sigma-2\omega}[e^{-2(1+i)\beta_1 h''}+e^{2(1+i)\beta_1 h'}]A_1''$$
$$=\frac{1}{2}\frac{\Delta\rho}{\rho}[1-e^{2(1+i)\beta_1 h''}]$$
$$-\left(\epsilon+\frac{\Delta\rho}{\rho}\right)e^{-(1+i)\beta_1 h''} \quad (17)$$

$$\frac{2\epsilon}{\sigma-2\omega}[e^{-2(1+i)\beta_1 h'}+e^{2(1+i)\beta_1 h''}]A_2'$$
$$=\frac{1}{2}\frac{\Delta\rho}{\rho}[1+e^{2(1+i)\beta_1 h''}]$$
$$-\left(\epsilon+\frac{\Delta\rho}{\rho}\right)e^{(1+i)\beta_1 h''} \quad (18)$$

$$\frac{2\left(\epsilon+\frac{\Delta\rho}{\rho}\right)}{\sigma-2\omega}[e^{-2(1+i)\beta_2 h'}+e^{2(1+i)\beta_2 h''}]A_2''$$
$$=\frac{1}{2}\frac{\Delta\rho}{\rho}[1-e^{-2(1+i)\beta_2 h'}]$$
$$-\left(\epsilon+\frac{\Delta\rho}{\rho}\right)e^{(1+i)\beta_2 h''} \quad (19)$$

$$\frac{2\epsilon}{\sigma+2\omega}[e^{-2(1+i)\beta_2 h''}+e^{2(1+i)\beta_2 h'}]A_3'$$
$$=-\frac{1}{2}\frac{\Delta\rho}{\rho}[1+e^{-2(1+i)\beta_2 h''}]$$
$$+\left(\epsilon+\frac{\Delta\rho}{\rho}\right)e^{-(1+i)\beta_2 h''} \quad (20)$$

$$\frac{2\left(\epsilon+\frac{\Delta\rho}{\rho}\right)}{\sigma+2\omega}[e^{-2(1+i)\beta_2 h''}+e^{2(1+i)\beta_2 h'}]A_3''$$
$$=-\frac{1}{2}\frac{\Delta\rho}{\rho}[1-e^{2(1+i)\beta_2 h'}]$$
$$+\left(\epsilon+\frac{\Delta\rho}{\rho}\right)e^{-(1+i)\beta_2 h''} \quad (21)$$

$$\frac{2\epsilon}{\sigma+2\omega}[e^{-2(1+i)\beta_2 h'}+e^{2(1+i)\beta_2 h''}]A_4'$$
$$=-\frac{1}{2}\frac{\Delta\rho}{\rho}[1+e^{2(1+i)\beta_2 h''}]$$
$$+\left(\epsilon+\frac{\Delta\rho}{\rho}\right)e^{(1+i)\beta_2 h''} \quad (22)$$

$$\frac{2\left(\epsilon+\frac{\Delta\rho}{\rho}\right)}{\sigma+2\omega}[e^{-2(1+i)\beta_2 h'}+e^{2(1+i)\beta_2 h''}]A_4''$$
$$=-\frac{1}{2}\frac{\Delta\rho}{\rho}[1-e^{-2(1+i)\beta_2 h'}]$$
$$+\left(\epsilon+\frac{\Delta\rho}{\rho}\right)e^{-(1+i)\beta_2 h''} \quad (23)$$

where ϵ is a small quantity for internal waves.

The equations of continuity can now be written

$$\int_0^{h'}\zeta_0'(\gamma^2+2ik\gamma-k^2)f'(z)\,dz$$
$$=i\sigma(\zeta_0''-\zeta_0') \quad (24)$$

and

$$\int_{-h''}^{0}\left(\zeta_0'+\frac{\Delta\rho}{\rho}\zeta_0''\right)$$
$$\cdot(\gamma^2+2ik\gamma-k^2)f''(z)\,dz=-i\sigma\zeta_0'' \quad (25)$$

where

$$f'(z)=\frac{ig}{\sigma^2-4\omega^2}[\sigma+A_1'e^{(1+i)\beta_1 z}$$
$$+A_2'e^{-(1+i)\beta_1 z}-A_3'e^{(1+i)\beta_2 z}-A_4'e^{-(1+i)\beta_2 z}]$$

and

$$f''(z)=\frac{ig}{\sigma^2-4\omega^2}[\sigma+A_1''e^{(1+i)\beta_1 z}$$
$$+A_2''e^{-(1+i)\beta_1 z}-A_3''e^{(1+i)\beta_2 z}-A_4''e^{-(1+i)\beta_2 z}]$$

Integration of the equations of continuity and substitution of the values for the constants A yields the following two expressions in $(\gamma+ik)$ and ϵ

$$\frac{\left(1-\frac{\Delta\rho}{\rho}\Theta\right)}{R}$$
$$=\frac{p\sinh[(1+i)\beta_1 h']\cdot\{\cosh[(1+i)\beta_1 h'']+1\}}{(1+i)B_1\cosh[(1+i)\beta_1(h'+h'')]}$$
$$+\frac{q\sinh[(1+i)\beta_2 h']\cdot\{\cosh[(1+i)\beta_2 h'']+1\}}{(1+i)B_2\cosh[(1+i)\beta_2(h'+h'')]}$$
$$+\Theta\left\{\frac{h'}{h'+h''}+\frac{p\sinh[(1+i)\beta_1 h']}{(1+i)B_1\cdot\cosh[(1+i)\beta_1(h'+h'')]}\right.$$
$$\left.-\frac{q\sinh[(1+i)\beta_2 h']}{(1+i)B_2\cosh[(1+i)\beta_2(h'+h'')]}\right\} \quad (29)$$

$$\frac{\frac{\Delta\rho}{\rho}\Theta}{R}=-\frac{h''}{h'+h''}$$
$$p\{\sinh[(1+i)\beta_1 h']$$
$$-\frac{+\sinh[(1+i)\beta_1(h'+h'')]\}}{(1+i)B_1\cosh[(1+i)\beta_1(h'+h'')]}$$
$$q\{\sinh[(1+i)\beta_2 h']$$
$$-\frac{-\sinh[(1+i)\beta_2(h'+h'')]\}}{(1+i)B_2\cosh[(1+i)\beta_2(h'+h'')]}$$
$$+\Theta\left\{\frac{q\sinh[(1+i)\beta_2(h'+h'')]}{(1+i)B_2\cosh[(1+i)\beta_2(h'+h'')]}\right.$$
$$\left.-\frac{p\sinh[(1+i)\beta_1(h'+h'')]}{(1+i)B_1\cosh[(1+i)\beta_1(h'+h'')]}-1\right\} \quad (27)$$

These equations can be solved for any given values of σ, ω, ν, h', h'', and $\Delta\rho/\rho$. However, a particular numerical solution will not indicate the dependence of k, γ, ζ_0', and ζ_0'' on the above independent variables. For the most important range of variables it is possible to approximate the relations to give functional relationships between the above quantities.

The following ranges of variables will be considered, using cgs units: $h' > 5 \times 10^3$, $5 \times 10^5 > h'' > 10^5$, $1 < \nu < 10^3$, $\Delta\rho/\rho < 10^{-3}$, $\omega < 0.725 \times 10^{-4}$, $0.725 \times 10^{-4} < \sigma < 3 \times 10^{-4}$, with the additional restriction that

$$\sqrt{(\sigma - 2\omega)/2\nu}\, h' > 1.2. \tag{28}$$

The unknown quantities are now split into real and imaginary parts

$$R = S + iT = S_0(1 + S_1 + iT_1) \tag{29}$$

$$\Theta = \Phi + i\Psi = \Phi_0(1 + \Phi_1 + i\Psi_1) \tag{30}$$

where S_0 and Φ_0 are the approximate limiting values for the unknowns when $\nu \to 0$. Upon substitution of these expressions into (26) and (27), and introduction of P and Q, the result to first-order terms in S_1, T_1, Φ_1, and Ψ_1 is

$$\begin{aligned}(S_1 + iT_1) = {} & \frac{\Delta\rho}{\rho}\frac{h''}{h' + h''}\left(1 - \frac{h'}{h' + h''}\right) \\ & + \left\{\frac{(h' + h'')^2}{h'h''} - \frac{h'}{h''}\right\} P \\ & + \left\{\frac{(h' + h'')^2}{h'h''} + \frac{h'}{h''}\right\} Q \\ & - i\left\{\frac{(h' + h'')^2}{h'h''} + \frac{h'}{h''}\right\} P \\ & - i\left\{\frac{(h' + h'')^2}{h'h''} - \frac{h'}{h''}\right\} Q \end{aligned} \tag{31}$$

$$\begin{aligned}(\Phi_1 + i\Psi_1) = {} & \frac{\Delta\rho}{\rho}\frac{h'h''}{(h' + h'')^2} + \frac{h'}{h''}(P - Q) \\ & - i\frac{h'}{h''}(P - Q) - (P + Q)\frac{\Delta\rho}{\rho} \\ & + i\frac{\Delta\rho}{\rho}(P + Q). \end{aligned} \tag{32}$$

Now the following expressions can be written for the unknowns

$$\begin{aligned}& g\frac{\Delta\rho}{\rho}(h' + h'') \\ & \frac{}{\sigma^2 - 4\omega^2}(\gamma + ik)^2 \\ & \qquad = -\frac{(h' + h'')^2}{h'h''}(1 + S_1 + iT_1) \end{aligned} \tag{33}$$

and

$$\frac{\epsilon}{\Delta\rho/\rho} = -\frac{h''}{h' + h''}(1 + \Phi_1 + i\Psi_1) \tag{34}$$

In most cases of interest the terms in (31) and (32) containing $\Delta\rho/\rho$ will be negligibly small and $h'/h'' \ll (h' + h'')^2/h'h''$. They then can be written

$$(S_1 + iT_1) = \frac{(h' + h'')^2}{h'h''}(P + Q)(1 - i) \tag{35}$$

$$(\Phi_1 + i\Psi_1) = \frac{h'}{h''}(P - Q)(1 - i) \tag{36}$$

Approximate solutions of these equations for the wave number k and the damping coefficient γ of the internal waves are

$$\begin{aligned}k = {} & \sqrt{\frac{(\sigma^2 - 4\omega^2)(h' + h'')}{gh'h''\Delta\rho/\rho}} \\ & \left\{1 + \frac{(h' + h'')\nu^{\frac{1}{2}}[(\sigma - 2\omega)^{\frac{1}{2}} + (\sigma + 2\omega)^{\frac{1}{2}}]}{4\sqrt{2}h'h''\sigma(\sigma^2 - 4\omega^2)^{\frac{1}{2}}}\right\} \end{aligned} \tag{37}$$

$$\begin{aligned}\gamma = {} & \left(\frac{\nu}{2g\Delta\rho/\rho}\right)^{\frac{1}{2}}\left(\frac{h' + h''}{h'h''}\right)^{\frac{1}{2}} \\ & \cdot\left\{\frac{(\sigma - 2\omega)^{\frac{1}{2}} + (\sigma + 2\omega)^{\frac{1}{2}}}{4\sigma}\right\} \end{aligned} \tag{38}$$

The solution for ϵ is then

$$\begin{aligned}\epsilon = {} & -\frac{\Delta\rho}{\rho}\frac{h''}{h' + h''}\left[1 - \frac{h'}{h''}\right. \\ & \left.\cdot(1 - i)\frac{(2\nu)^{\frac{1}{2}}\{(\sigma + 2\omega)^{\frac{1}{2}} - (\sigma - 2\omega)^{\frac{1}{2}}\}}{4\sigma(h' + h'')(\sigma^2 - 4\omega^2)^{\frac{1}{2}}}\right] \end{aligned} \tag{39}$$

The approximations used are valid when both of the following conditions are satisfied: γ is small compared to k, and the second term in parentheses in (37) is small compared to unity.

Discussion of results—The wave number k is increased; thus wave length and velocity are decreased by the effect of eddy viscosity. The correction term in the expression for the wave number varies as the square root of the eddy viscosity, and inversely as the depth of the shallower layer. Its magnitude is small unless the restriction of (28) is violated by approach to the inertial period.

The damping coefficient γ varies directly as the square root of the eddy viscosity, and inversely as both the square root of the density difference and the three-halves power of the depth of the shallower layer. It increases approximately as the square root of the frequency but has only small de-

TABLE 1 – *Representative values of wave number and damping coefficient*

L	T	h′	h″	ν	Δρ	k	γ
°	hr	m	m	cm²/sec	g/cm³	km⁻¹	km⁻¹
50	12	100	1000	100	10^{-3}	.10	6.0×10^{-3}
30	12	100	1000	100	10^{-3}	.14	5.4×10^{-3}
15	12	100	1000	100	10^{-3}	.15	5.0×10^{-3}
15	24	100	1000	100	10^{-3}	.058	3.2×10^{-3}
15	24	100	1000	10	10^{-3}	.056	1.0×10^{-3}
15	24	100	1000	1	10^{-3}	.055	0.32×10^{-3}
15	24	500	1000	1	10^{-3}	.027	0.045×10^{-3}
15	24	100	1000	1	2×10^{-3}	.039	0.23×10^{-3}
0	12	100	1000	1	10^{-3}	.15	0.49×10^{-3}
0	24	100	1000	1	10^{-3}	.076	0.35×10^{-3}

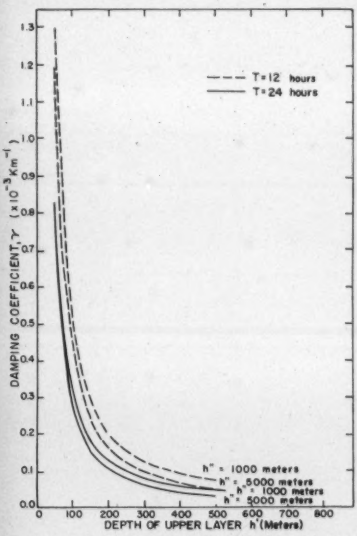

FIG. 1 — Damping coefficient variation with layer depth (L = 15°, $\nu = 1$ cm² sec $^{-1}$, $\Delta\rho = 10^{-3}$ gm cm^{-3})

pendence on latitude in the range under consideration.

The ratio of free surface to interface displacement is decreased in magnitude by friction with a decrease in time lag for the free-surface motion. Again the correction terms vary directly as the square root of the eddy viscosity and are small unless the inertial period is approached.

Representative values for k and γ under various typical conditions are given in Table 1.

The distribution of internal waves will depend very strongly on the value of the damping coefficient, γ. This quantity varies from a maximum of 6.0×10^{-3}/km to a minimum of 0.045×10^{-3}/km for the conditions considered. That is, wave amplitudes would be decreased by 50 pct in distances of 120 km and 15,000 km respectively. The actual distance of wave travel will depend strongly on the prevailing oceanographic conditions and the wave period, but not on the latitude within the restrictions of (28).

Let us consider a typical example. Since the depth of maximum stability is that of maximum velocity shear, the effective eddy viscosity is taken to be 1 cm²/sec. An average value of 100 m is used for the upper layer depth, and 10^{-3} g/cm³ for the density difference across the interface. Then, at latitude 15° N, k and γ will be 0.15 km^{-1} and 0.50×10^{-3} km^{-1} respectively for a 12-hr period, and 0.055 km^{-1} and 0.32×10^{-3} km^{-1} for a 24-hr period. The 12-hr and 24-hr waves have wave lengths of 42 km and 110 km respectively, and distances for a 50-pct amplitude decrease of 1400 km and 2100 km. Figure 1 shows the variation of γ with the depths of the upper and lower layers. These results are of the right order of magnitude to give regions of strong internal waves surrounding bottom irregularities, and yet are not small enough to give standing waves over the entire ocean.

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Water Supply and Drainage in Semi-Arid Countries

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Abstract—Drainage cannot be separated from water supply for land development in hill-plain border regions of semi-arid countries. In order to avoid economic and technical *cul de sacs*, resulting from the usual procedures of amelioration, drainage should be considered a residual engineering task, incidental to and following the use of water resources.

If it is desired to irrigate a maximum area of land, a priority of sequences must be fixed at an early stage for the measures taken to exploit successively the total inventory of surface and subsurface waters. A general scheme of priorities establishes the following precedences: (a) water supply before drainage and flood control, (b) use of subsurface before surface waters, (c) abstraction from foreland ground-water horizons before mountain ground water, (d) development of hill before valley springs, and (e) use and creation of underground storage before surface storage.

It is not possible to devise a rational drainage scheme and to plan the maximum exploitation of local water resources without operating wells on a year-round basis. If this premise is accepted, wells must be sited and installed so as to serve several purposes: (a) to extract the average annual replenishment and gradually most of the fossil reserve, (b) to drain marshy lands in the plain, (c) to accept recharge from winter-spring flows, floods, and foreland wells, and (d) to extract subsurface winter flow in the foreland and to recharge it into mountain wells (recycling).

Introduction—A methodical approach to the optimal development of land and water resources in semi-arid zones should be highly critical towards experiences gained in humid countries as regards the direct beneficial use of water from springs, rivers, drainage works or floods and as regards surface storage.

For the retention of large water quantities the alternatives of surface and subsurface storage have to be considered on the basis of comparable technical and economic data. This involves, in the first instance, a thorough study of subsurface conditions by modern exploration techniques. As a rule, subsurface storage capacity transcends the easily available storage possibilities on the ground. Since keeping water underground also reduces evaporation and permits a gradual expansion of the storage volume these advantages may frequently outweigh the benefits derived from the construction of the more conventional structures above ground.

The stress laid in this paper on the exploitation of the subsoil as a source of water supply and a medium for storage reflects the growing consciousness among water engineers and Earth scientists that reservoir formations of the subsoil represent the great protecting, stabilizing, and equalizing element in the hydrological cycle on land.

In arid and semi-arid zones we frequently observe a baffling juxtaposition of large land reserves with insufficient sources of irrigation water and wide water-logged areas, swampy either periodically or throughout the whole year. Water surplus under these conditions is due to the concentration of precipitation during a short rainy season and to undeveloped natural surface and subsurface drainage. The fact that irrigation by itself often contributes to saturation of the soil with water and salts will not be discussed here.

Bringing new land under the plow and expanding the irrigated area necessitates drainage works besides the full exploitation of surplus waters. Taking a typical setup of geohydrological circumstances as an example, we want to show that the solutions hitherto applied to the problems of water supply and drainage usually lead to technical or economic *cul de sacs*. Only the inclusion of artificial recharge within a proper sequence of well calculated steps of amelioration will result in a complete development of land and water resources. The form of recharge recommended constitutes a kind of artificial hydrological cycle. It not only prevents the waste through evaporation of precious water reserves in arid zones but also permits the rational use of swampy lands. Man thus sets in motion a process of exploiting and 'creating' water resources at the same time, a process which closely resembles the productive cycle initiated by erosion-preventing measures and by good soil management. The setup selected for discussion may be regarded as characteristic for long belts of semi-arid

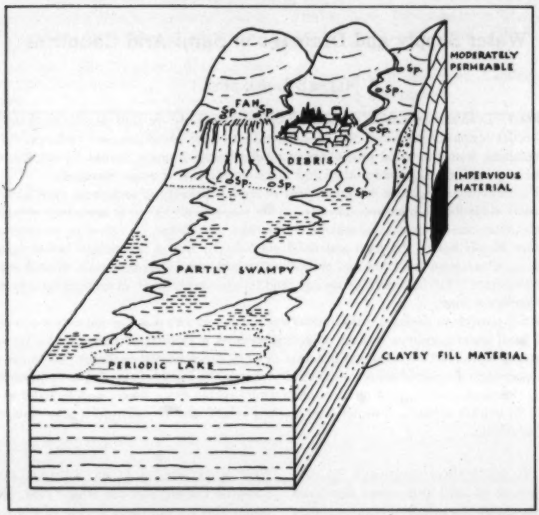

FIG. 1 – Generalized geohydrologic setup near a mountain border of semi-arid zone

mountain border lands, facing the direction of the internal drainage in the major continents.

The geohydrological context—Our example presupposes the existence of a mountain massif consisting of moderately permeable sedimentary rocks, turning a flank towards an alluvial valley floor. The valley drops at a slight gradient to its drainage base: a seasonally dry river system (creek, wadi) or a periodically expanding swamp, lake, mud plain, or shott. The formations building up the valley to great depth consist of alluvial soil, underlain by clays, marls, shales; coarse debris blankets a narrow zone along the foothills and builds the fans which protrude from the massif. We imagine the contact between the mountain and valley formations as a simple or complicated fault or a more or less steeply dipping monocline of the consolidated layers, against which the younger sediments are placed.

With a rainfall of 300–600 mm per annum (lower precipitation in the plain and higher in the hills) springs will occur in the partly permeable areas in the mountains and in the upper parts of the plain (see Fig. 1). The concentration of rains in three to five months causes periodic strong surface runoff, flooding, and swamp conditions, developing particularly in the lower levels. The state of oversaturation recedes in the course of the long dry summer months; however, on the heavy soils it may be partially retained as a result of the deep-reaching high summer-temperature effect on capillary openings [*Terzaghi*, 1942].

Surface runoff, according to size and duration, takes three forms: (a) short and sudden floods as the direct result of concentrated rainfall, (b) runoff following prolonged precipitation, resulting from direct rainfall as well as from short-term subsoil storage (seepage, increases in yield of small and large springs), (c) runoff following prolonged precipitation, but caused by the delayed discharge through the main springs after the major aquifer has been filled.

Springs may be divided into three types: (a) mountain springs caused by favorable local structural or lithological conditions and to the reappearance of percolated waters from springs of higher level, (b) foothill springs emerging at the contact between hill and valley formations, springs in the foreland and the plain, emerging from a fan or in the lower part of the plain along a terrace near the contact of debris and the less permeable valley fill.

The types of underground water which we may expect are: (a) underground water in the moder-

ately permeable mountain formations (one or several above a thick impermeable substratum), (b) underground water in the valley fills and in the fans, and (c) underground water in very slow motion in the clayey sediments of the lower plain.

Swamp conditions in the mountains are restricted to the neighborhood of seeps and springs; likewise in the upper parts of the plain because of loose texture of the subsoil. At the border zone of the deep plastic soil swamps will be connected, in the form of broad patches or belts, with the spring areas. Extensive swamps will develop in the lower portions of the plain made up of impermeable clays and marls, and remain in a more or less severe form permanently.

Agriculture under semi-virgin conditions and early development work—Human settlement is apt to start in the foothill zone, where factors combine to encourage agriculture. The lower reaches of the hills serve as an outlook into the mountains and over the plains and protect a community from attack. The same geographical position affords protection from flooding and adverse health effects of a shallow water table. Conditions for domestic water supply will range from good to excellent: gravity flow may be expected from springs in the mountains; permanency of yield from springs and from bore holes is best assured in the vicinity of the foothill zone.

The good and large soil areas are concentrated in the plain, with the best drained belt placed against the mountain border. Here the agricultural conquest of the whole region will start; progress in the direction of the narrow hill valleys involves development problems in terracing and small-scale land exploitation; progress in the direction of the center of the plain has to battle with difficulties of drainage and procuring sufficient quantities of irrigation water for large-scale agricultural production.

On land where periodic swamp conditions develop in winter the agricultural season is limited to summer. Excessive soil moisture in the lowland may continue into the summer, thus shortening still further the operative farming period. Consequently, the use of the main land reserve will be limited to growing crops during a few months only.

In the higher, well drained reaches of the plain permanent plantations may be set up. However, since the boundary between the upper and lower portions of the plain may be difficult to establish and since it fluctuates in dry as well as in wet years, damage to plantations is sometimes unavoidable.

The cheap and readily available water resources are obviously the first to be used for irrigation: the summer flow of springs and shallow wells in the plain. Once these are exploited at capacity, water will become scarce towards the end of the irrigation season, when the demand is greatest and the spring flow at its lowest. The reduction in yield of springs runs parallel to a lowering of the water table in wells, so that after poor rainfall years or during delays in the first rains catastrophic conditions may arise. The farming community is then placed between hammer and anvil: either to gamble on good or average water yields of springs and wells and to face losses from more or less frequent droughts, or to be careful with the expansion of irrigated orchards or crops and to forego the gains from plentiful though irregular water supplies.

In a progressive agricultural society, after this stage of development has been concluded, one or several spirals of new growth may be set in motion, leading through increased water supplies and drainage to an extension of the irrigated area.

The improvement of spring flows entails the cleaning of the discharge openings and pools, the building of storage facilities for night and, later on, for winter flows, and the construction of lined open conduits or the laying of pipelines. Geographically this work will start at the springs at the lower topographical level nearest to the villages and in the fields in the upper parts of the plain, and then proceed to the higher mountain springs. Domestic consumption will probably be based on the springs, since the quantities needed are small, and a spring appears as a safe and cheap (gravity flow) source of supply.

When a fair control of spring flow has been reached, the farmer will turn his steps to draining the periodically swampy valley lands. This will be relatively easy and successful in the light soils near the mountain border, but rather complicated and only partially successful in the heavy soils. The further his drainage work penetrates into the low-lying valley lands, the smaller becomes his reward in effectively desiccating them. Under the prevalent geohydrological circumstances water saturation in the latter case is due to a minor degree only to slow downward drainage of rain and flood water in an impermeable medium and more to sluggish movement of ground water with high capillary rise [*Simpson*, 1934] fed from a wide catchment area. On-the-spot drainage works (ditches, clay pipes, buried permeable beds) may decrease excess moisture from the first cause but

lose out in the fight against the second, more decisive factor. The main questions which face the farmer or the water engineer in this situation concern the dimensions and the depth of the drainage channels and their density per area unit.

Probably the limitations of normal drainage work will not become apparent except at a late stage of land amelioration. Long before, the search after additional water resources for irrigation will overshadow the demand for soil improvement, because in semi-arid countries in general and under the circumstances envisaged by our example in particular, the main limiting factor for the rise in living standards is water, not land.

Naturally, attention will be directed (besides to springs) to the other type of surface water resources, winter runoff in the wadis. A close examination of this source reveals that little margin exists between normal or increased spring flow as the result of periodic rainfall, which we consider to have been controlled under various schemes of spring-water exploitation, and flash floods, the typical form of runoff in arid zones, which can be tamed and used only at great cost and give relatively small direct economic gain [*Lowdermilk*, 1953a]. Unless conditions for the storage of all winter floods are exceptionally favorable, we may assume that the management of spring flows as described above represents an important achievement in the exploitation of surface runoff. Beyond this, early development work is likely to concentrate its efforts more on preventing damage to fields from storm flow than on erecting big structures for their collection. The preventive measures consist in increasing the height of banks and in straightening and deepening the stream channel.

The drilling of wells may progress from a haphazard location of bore sites to a full-fleged systematic drilling campaign, preceded and accompanied by the modern tools of geohydrological, geophysical and engineering techniques. Drilling will proceed from the plain and foreland into the mountain valleys. In the fans and the gravelly or sandy portions bordering the foothills the water table is near the surface, the irrigated fields are close to the pumps, and the bore holes shallow. With the pressure of further water demands the drill moves into the mountainous area to exploit the consolidated formations building the hills. Advantageously, wells will be placed near the valley border to shorten the distance to the area of water consumption, to avoid high pumping head and to penetrate the favored horizons of concentrated subsoil drainage.

The means of land amelioration and the steps of increasing water supplies lead to a 'plateau' of developing agricultural land resources. Swampy areas near the mountain springs are eliminated; drainage works near the valley springs and the pumpage from wells will have reduced swamp conditions in the plain; damage from floods has been limited. Available quantities of water have greatly increased through use of drainage water, through improved spring openings, through wells exploiting the main ground-water horizons during the irrigation season.

The critical conditions for land and water development—The plateau of improvement described at the end of the preceding paragraph will not be reached at one and the same time by all steps of land amelioration and water supply alike. It rather represents an average level of achievement towards which a guided development policy tends. Sooner or later flaws may show up, when each of the single stages is pursued to its logical end. Here we arrive at critical conditions which slacken and complicate further progress or burden the agricultural communities with the reversal of development policies. Before enumerating some of these quite common *cul de sacs* we must formulate the ultimate purpose of land use and water supply under the set of circumstances on which our discussion is based. The rural economy aims at: (1) elimination of swamp conditions around all spring areas; (2) elimination of swamp conditions caused by perennial sub-surface flow in the plain; (3) reduction of swamp conditions caused by direct winter rains, floods and increased winter subsurface flow; and (4) maximum use of water from all sources of supply taken together, directed for irrigation during the dry season.

If social conditions exist whereby the land users within a sufficiently large geographical unit cooperate in a regional development scheme, these ultimate aims can be attained; they are, however, not reached, except under heavy sacrifice, through the usual means of amelioration and water supply described in the preceding chapter, and not through the sequence of steps which lead to a plateau of development.

The blind alleys on the plateau may be characterized by the following contradictions:

(1) The development of and the installations provided for springs in the lower parts of the mountain valleys may become redundant when the

higher springs are developed later or at the same time and when it turns out that the low-level yield largely represents a resurgence of the upper spring flows.

(2) Installations for the springs on the border of thick clay fills may become superfluous when these springs decrease in volume or dry up as a result of pumping from wells which intercept the subsoil spring flow.

(3) If flood control has at first been met with by straightening and deepening the wadi bed, later measures for positively exploiting floods must try to decrease the flow gradient and to lengthen the stream course, in order to increase the time and area of contact between water and ground for purposes of recharge and storage.

(4) Relations which complicate the exploitation of springs at different topographical levels may similarly govern the hydrological regime between wells in the higher and the lower regions. Original yields of wells may decrease in the course of years and become the source of costly readjustment in the pumping, conducting, and storing installations.

(5) The quantitative relations between cyclic and fossil subsoil water reserves can only vaguely be determined in advance of systematic drilling and pumping campaigns. It is therefore difficult in the constructive stage to determine safe yields, final drawdowns, and rest levels for individual wells. Wells initially good may become marginal producers. The slow clarification of the relations between average optimum yields at the end of the rainy season (when no or little water is extracted for irrigation and when nature supplies its maximum addition to reserve) and the end of the dry season (when record quantities are needed and when the total reserve stands at its lowest level) also complicates efficient planning.

(6) Drainage channels at first dug to a small or moderate depth may become obsolete when the water level in the plain sinks below their bottom as a result of spring exploitation and ground-water pumpage.

While we concede that some of the cited complications arising in the course of a combined drainage and water-supply operation may be foreseen and partly prevented on the basis of a comprehensive geohydrologic analysis including test drilling and test pumping, some apparently fundamental contrasts seem insoluble: (1) the desire to exploit winter surplus surface and subsoil water and the great costs in providing surface storage for a summer with high evaporation rates; (2) the need to eliminate swamp conditions on heavy soils, which become saturated not only during the rainy period but also during the dry season from slowly flowing and rising ground water; to prevent soil saturation under these circumstances it would be necessary to abstract ground water during the whole year, which would still further increase the complications mentioned under (1).

The only way out of the difficulty is the provision and use of subsurface storage in natural reservoirs and the year-round interception of subsurface flow before it enters the heavy soil area. Neither of these two steps can arbitrarily be introduced at any desired time or stage of a normal development program, such as has been described here. They have to be part of a concept, ready to interfere radically with the natural hydrologic cycle, and to be applied from the outset to the whole sequence of water-supply and drainage schemes; governing a regional hydrological unit.

Established practices rarely represent logical steps leading gradually to full land use and the maximum exploitation of water resources. At best they express a short-term agricultural development policy. Costs for such steps may largely have to be written off during the main and final stage of amelioration, because the technical structures and installations, built for an initial or intermediate stage, may later on either be changed fundamentally or abandoned.

The sequence of priorities for land and water development—The system of priorities which needs to be established is discussed here for a generalized problem. As we shall find out, the sequence of priorities follows not a single road of development but a path, where, occasionally, several lines of amelioration may be pursued simultaneously.

Water supply and drainage—The first basic succession of priorities to be accepted divides between water supply from spring and subsoil horizons on the one side and drainage and flood control on the other. Precedence of water supply over drainage is indicated for several reasons: (1) Under semi-arid conditions irrigation acts as a prime force to expand agricultural production. Rainfall alone during a short period leaves the land fallow for the major part of the dry season. The same unit of land adds several times of its value if it is irrigated. (2) In semi-arid countries the water demand for irrigable land reserves usually exceeds the quantities of easily accessible summer water resources. (3) Any abstraction of water for

domestic or agricultural purposes represents in itself a drainage process, insofar as it diminishes the flow of water into the heavy-soil areas.

Flood control, because of its many hazards and its partial dependence on normal spring and ground-water flows, may be treated as a residual technical task, similar to drainage. The use and storage of spring and ground water for irrigation, particularly if it is extended into the wet season, frees the subsoil for additional storage during storm runoff and decreases flood quantities by the same amount which is taken from the regular surface spring flow. Therefore, increased exploitation of spring and ground water represents at the same time a basic start both for flood control and for dewatering of swamps.

Ground-water and spring exploitation—The second succession of priorities regulates the relations between springs and ground water and establishes the priority of ground-water exploitation to the use of spring flows. Since springs represent either an outflow or overflow of a subsoil water horizon the optimum extraction from the subsoil will lower the water table, temporarily and permanently, and necessarily decrease, in extreme cases even stop, spring yields. In an ultimate stage of water use, springs may thus be considered a marginal quantity of ground water, freely reaching the surface of the land, while the ground-water horizons are exploited at optimum capacity.

However, the precedence of ground water before spring development cannot be regarded as a principle guiding all phases of development in the same manner and applying to all types of springs equally. The relations between ground water and spring exploitation appear in a different light when we examine them in the hills or in the plain; we also find different solutions when we discuss this relationship with regard to summer flows and to quantities of spring water stored from the rainy period for the dry-weather irrigation season.

In order to clarify these points further we have to go back to fundamental hydrological data. The three geographical zones—hills, foreland, and plain—contain various types of springs and ground water of different characteristics as regards the thickness and stratification of the aquifer, the position and gradient of the water table, the speed of movement of the subsoil flow. These properties influence the relation between water supply, drainage and recharge differently in time and space.

In the hills, built of moderately permeable sedimentary rocks, ground water is expected to move in several horizons with unequal potentials; waterbearing layers reach down to several hundred meters below the level of the drainage base; because of the elevated topography the water table lies relatively deep; the water-table gradients are moderately or strongly inclined in the direction of the flow at a rate of at least several meters per kilometer.

In the foreland, the belt of highly permeable debris including the fans contains fairly quickly moving ground water in a single horizon and there will be a flat gradient of the water table.

In the plain, we have assumed no water-bearing layers of practical significance for exploitation by wells. Nevertheless, the colloidal sediments of high porosity and low permeability are water-saturated from the sources enumerated before. The water moves extremely slowly, the horizontal movement being impeded both by the small size of the pores and by the summer upward rise. The water table stands either near the surface or at a very shallow depth, and its gradient follows more or less the surface contours.

If we place the springs, which we consider as border phenomena of ground-water occurrences, into the hydrological context of the subsoil water movement described above, we obtain the following constellation:

There are springs in the hills, particularly in the higher elevations; if they are of the outflow (not overflow) type, they may drain an entire groundwater aquifer. In the low levels and at the foot of the mountains their hydrological character becomes complex: outflow and overflow from a porous section of the massif will mix with percolation from a higher aquifer or with mountain ground water banked up against a nonpermeable fault zone, which at the same spot may also arrest wadi-under-flow. The hydrological complexity increases still further for the springs of the foreland and for the upper part of the plain, where they flow from fans and other coarse debris. The geological situation of these latter sources may appear simpler, but it will often be difficult to determine the quantitative participation of ground water from several sources, of geniune underflow from wadis and of underflow originating from lost springs from a higher topographical level.

The characterization and interrelation of groundwater zones and of springs, which we have followed up so far, now permit a further graduation of priorities for ground water and spring development, separately and jointly.

Use of mountain and foreland ground water—The

foreland ground-water zone requires priority in exploitation to the two neighboring ground-water areas for the following reasons: (1) From the point of view of water-supply development it forms the main receptacle of the regional ground-water resources. Further down the subsoil water cannot be extracted by wells in quantity because of low permeability. Up in the hills ground-water joins the foreland horizon, unless it appears at springs or dissipates in local marshy patches. (2) In terms of drilling and pumping costs as also of convenience for water transport to irrigable lands the foreland belt lies geographically most favorable. (3) Water abstraction in the foreland drains more directly and effectively the saturated soils of the plain than ground-water exploitation in the hills.

The siting of boreholes in the outwash zone is more difficult than in the hills because of the lack of outcrops and of other indications for the configuration and composition of the subsoil. Under these circumstances an extensive use of geoelectric measurements is needed to determine the thickness of the aquifer, to distinguish between coarser and less permeable deposits and generally to delineate the boundaries of the water-bearing layers.

Since the well field of the foreland exploits ground water partly derived from one or all of the hill horizons, it might be asked whether additional bores are required in the hills. This question is to be answered in the affirmative on the following grounds: (1) The mountains, containing several aquifers, have accumulated a considerable reserve in the course of geological time which may surpass the annual average replenishment by a factor of about ten [*Piper*, 1953]. The reduction of this so-called one time reserve will make available not only large quantities of water for consumption but will also increase natural infiltration through the flattening of the flow gradient, through reduction of surface seepage and through the freeing of storage volume. (2) The provision of subsurface storage space in the hills and of boreholes acting as conduits for recharge in winter (in summer also as wells for extraction) serves as an indispensable link in conserving surplus water of the rainy season. (3) Subsurface storage has to be created at some distance from the marshy plain, so that the pressure of ground-water flow into the heavy soil is relieved. Subsoil storage in the hills will be used mainly to receive winter-spring flows and pumped ground water from the wells of the foreland at a time when no need for irrigation exists.

It is clear from the above that bore holes in the hills have to penetrate the whole section of water-bearing layers, that is, all aquifers to the top of the main confining substratum. The siting of bore holes will in the main follow geological indications. The more favorable drilling areas are likely to be selected in the foot hill zone where permeability is usually highest. Here practical reasons may join the favors of nature: lower pumping and drilling depths, and lastly the relative nearness to the wells of the foreland which in winter act as supplier of water for injection into the hill wells.

Development of hill and valley springs—In discussing the hydrological character of the three main ground-water areas we stated that the number of sources of origin of the various ground-water units increases with growing distance from the watershed. The same rule applies *cum grano salis* to the several types of springs, but the consequences which we drew with regard to development work on ground-water horizons are almost opposite those for the springs. Precedence in the latter case has to be given to the hill sources, preferably to those at the higher elevation. The full use of these flows shall be undertaken during the first stages of development, antedating or running parallel to the exploitation of ground water, because of the small measure of causative dependence between both.

It is indeed desirable that the yields of the uppermost springs should be abstracted from the hydrological system at the earliest possible opportunity, in order to reduce the complexity of factors affecting surface and subsurface water occurrences at lower levels and thus to simplify calculations and plans.

On final analysis, designs should be made to extract at least as much ground water through wells in the foreland as to completely dry up springs issuing from unconsolidated layers, because, from a water conservation and land amelioration point of view, these emergences represent wasteful issues of ground water. Under semi-arid or desert conditions most springs not flowing from well defined openings in consolidated formations belong to this latter category. Ground water in a dry country, which comes into contact with a loamy or marly cover, before it approaches the surface, loses large quantities (in relation to the free yield of the spring) of water through evaporation from the soil and through evapotranspiration from uncontrolled plant growth, induced by the continued soaking of the ground from below. These processes have to be prevented or at least reduced in scope through the artificial lowering of the water table by extraction through wells, which penetrate

the aquifer in an area, where ground water is still protected from direct contact with the air and with the upper sun-drenched layers.

We therefore envisage spring development work proper mainly in the hill zones, progressing from higher to lower topographical levels, while leaving the management of the springs near the foothills and in the plain as an integral part of the ground-water manipulation in these areas.

The storing of night flows from the mountain springs may be left to small operative surface reservoirs, while the preservation of winter-spring yields would be one of the tasks of the invertable wells in the hill formations.

Alternatives of surface or subsoil storage—Recharge into natural formation reservoirs is a modern technique, although a few schemes for large towns, situated in the temperate zone near permanent rivers, were started already 50–100 years ago [*Buchan*, 1955].

As regards artificial subsoil storage in comparison with retention in surface reservoirs, priority belongs to the former within the frame of our present investigation. The physical and economic advantages of storage in natural subsurface reservoirs may be summarized as follows: (1) Prevention of evaporation as against losses of the order of 0.8 to three meters of depth from open water surfaces. (2) Lower costs, where conditions are favorable, and the possibility of distributing the investment over a longer period. (3) Higher security in relation to natural (earthquakes) or political (war) catastrophes. (4) A wider distribution of the reservoir area with enhanced possibilities for more convenient collection and introduction into the reservoir and for more economical extraction in the neighborhood of places of consumption. (5) A gradual increase in the use of subsurface storage space permits also the gradual extension of abstraction and more organic expansion of the irrigated culture.

Among the disadvantages which may be connected with subsurface storage the following factors might be cited:

(1) The planning and building of surface structures can be calculated more precisely and supervised more closely. The difficulties of exploiting subsurface storage space, however, are usually exaggerated by water engineers because of lack of experience and training in the manipulation of natural reservoirs. Technical education and the majority of practical work in the broad field of water management have in the past been concentrated on surface waters and surface structures. The growing consciousness, derived from improved methods of subsoil exploration, that the volume of exploitable underground water resources and the usable underground storage exceed the reserves above ground, and that the increasing safety in ground-water and subsoil reservoir control today is already anchored on well established scientific and technical knowledge, will remove many obstacles in the way of a true evaluation of merits and demerits. For the time being much progress could be achieved already, if planners were prepared to view the alternatives under comparative economic and engineering perspectives. One should not plan to base water-supply schemes on the use and transport of surface supplies, unless they are shown to be superior in quality, economy, convenience, and safety to those for ground-water exploitation. A similar alternative exists for the examination of subsurface reservoirs in competition with surface collectors. The alternatives, however, cannot appear real unless a scientific and technical effort is invested in subsurface exploration, comparative to that regarded as adequate to surface projects.

(2) Water stored underground is re-extracted by energy, while water impounded above ground may usually be released by gravity. When assessing the cost of energy needed to pump water from subterranean storage, one finds that the arrangement of invertable wells proposed for our setup in semi-arid zones contains some ameliorating features. As will be remembered we regard the mountain massif as the suitable area for multi-purpose wells: (a) to extract part of the annual replenishment, (b) to extract gradually most of the fossil reserve, (c) to relieve part of the pressure and the flow of ground-water which cause marsh conditions in the plain, (d) to swallow winter flow from hill springs, (e) to receive ground water for recharge from wells in the foreland during winter and (f) to recirculate for consumption in summer water taken in during the rainy season.

The costs of drilling wells, of installing and operating them must therefore be charged not only against the value of the water reextracted from subsoil storage but also against the compound gain inherent in their operation. In an analogous way the costs of drilling and operating the wells of the foreland during winter for recharge purposes have to be distributed over the range of advantages accruing to the draining of land and to supplying water in summer.

Flood control and drainage—Both may be regarded as residual phenomena in the process of land and water amelioration. This is the reason why we discuss them together in this last paragraph on the establishment of development priorities and less because of their causal relations. It will have been observed that the gradual exploitation of water resources as proposed in the preceding paragraphs and the progressive desiccation of overmoistened lands are not only closely interrelated but also represent phases of a development process, which increases water supplies in a hydrologically well ordered sequence, which removes causes rather than symptoms in the formation of marshy soils, and which also leads to the necessary minimum measure of flood control, economically justified in arid countries. The exploitation of the various ground-water horizons and springs indirectly drains the swamps and the marshy land. Indirectly it creates favorable hydrological prerequisites for flood control. These consist: (1) in the reduction of surface runoff through the year-round use of spring flows, (2) in the lowering of the water table and generally in the freeing of pore space through optimum pumpage from all ground water horizons (including abstraction first from the fossil reserve, later on from the partial replacement of this reserve by recharge).

The first has reached its limits at the end of the dry season, that is, in time for the subsurface reservoirs to receive increased percolation through their roofs from winter floods. While the increased amount of water, filtering down from the streambed as a result of the liberation of additional subsoil storage may not be large in relation to the volume of peak floods, the natural process of augmented percolation may artificially be intensified by the building of retention dams, by induced bank infiltration and by spreading. These practices are indeed the normal ones for artificial replenishment, particularly in humid and temperate zones with their rivers and lakes [*Gaudenberger*, 1950], representing an equivalent to the flash floods of the dry zones. In arid regions, the building of delaying dams and employing of spreading techniques assume paramount importance because of the great drawbacks of normal dams (irregularity of floods in time and volume, high silt and debris load, suddenness and power of flow, and significant evaporation losses [*Lowdermilk*, 1953b]. Our attention has thus to be directed to lead as large as possible a percentage of winter floods underground. In the hills this purpose may be attained by erecting numerous stone or earth walls across the wadis. Such dams, besides reducing erosion, creating new soil, and preventing flooding and silting up of fields on the lower levels, augment percolation. A similar, perhaps even more effective, recharge may be carried out in the foreland, where permeable wadi beds rest on equally permeable outwash all along the foothills, particularly in the fans, and where the area of contact between flood waters and underground reservoirs may be enlarged by spreading.

The examination of flood-control principles returns us to the same arguments, which we discussed in the previous paragraph with regard to the surface and subsurface storage of normal surface flows and pumped supplies from ground water. Again, the alternatives must first clearly be faced before decisions can be taken. *Prima facie*, the case for surface storage of floods appears sound, because it is the established practice in temperate zones, where modern water-engineering techniques were born. However, upon further thought, the drawbacks for higher dams in the arid zones setup under discussion are formidable, and it therefore appears more logical to start from an opposite assumption. As long as a considerable volume of normal winter floods can economically be controlled through land improvement (terracing, erosion protection, soil retention) and recharge (natural and artificial) the building of large surface dams must be viewed with scepsis. The rare peak floods in arid countries are almost impossible to impound (the long time interval between such record flows, steeply rising costs for storing above-average water volume, increased evaporation losses for quantities held over a one-year cycle), and this waste seems unavoidable. Under this aspect the damaging effects of peak floods may not be preventable, except in cases where a very high degree of development can justify the costs for their amelioration.

Upon the completion of the schemes described in preceding paragraphs, the main causes for swamp formation in the low lands will have been abolished: the damaging effects of uncontrolled spring flows emerging from unconsolidated layers, and the major portion of the flow of ground water draining from the hills and the foreland into the valley region. The still remaining moisture saturation in the heavy soils, derived from direct rainfall in winter and from uncontrolled or uncontrollable storm runoff may now be dealt with the normal

practices of on-the-spot drainage. The quantities of soil and subsoil water created by these two factors will be far smaller than those which would have to be extracted if the procedure of groundwater and spring control with the proposed artificial hydrological cycle were not introduced. Also the fact that the residual drainage work, still to be carried out, can almost completely be concentrated on seasonal phenomena, interrupted in their occurrence by a long dry period, makes for easier quantitative calculation and control.

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Some Problems in Non-Artesian Ground-Water Flow

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Abstract—This paper deals with problems relating to ground-water movement in aquifers under water-table conditions, and more particularly with the unsteady flow caused by variations in some boundary condition or in the replenishment from the ground surface. The cases to be treated are diagrammatically shown; the first refers to the flow between two reservoirs, and the second to the flow between a water divide and a reservoir.

The treatment will be based on the so-called Laplace transformation method, which is useful for solving some typical cases, often met in hydrology and various fields of engineering practice. Definite formulas are established, which include the effect of a moderately sloping bottom, and the inclination of the ground-water level is also taken into consideration. Separate formulas are given for the more simple case that the bottom of the aquifer is horizontal.

Theory

Differential equations—Consider a non-artesian ground-water stream flowing over a horizontal or moderately sloping bottom according to Figures 1 and 2. Let the aquifer be referred to a coordinate system, the positive axis of which is in the direction of the flow and coincides with the bottom. The aquifer is assumed two-dimensional and homogeneous throughout. Disturbing effects, caused by capillarity, air-cushioning of the replenishment, etc., are disregarded. The fundamental differential equation for the unsteady flow in such aquifers is, as well-known, presented by *Boussinesq* [1877]. Using the general nomenclature given in Appendix 1, Boussinesq's equation may be written (taking replenishment into account)

$$\frac{c}{\epsilon} \cdot \left[z \cdot \frac{\partial^2 z}{\partial x^2} + \left(\frac{\partial z}{\partial x} \right)^2 \right] - \frac{c\alpha}{\epsilon} \cdot \frac{\partial z}{\partial x} = \frac{\partial z}{\partial t} - p \qquad (1)$$

with

$$q = c \cdot z \cdot \left(\alpha - \frac{\partial z}{\partial x} \right) \qquad (2)$$

The symbol ϵ denotes that part of the porosity, which is interconnected and open to replenishment and may thus at least approximately be taken equal to the specific yield of the water-bearing material. The symbol p means the 'speed' of the replenishment to the water table, that is, the rate of recharge or draft within the soil.

It may be noted that (1) is based on Dupuit's assumption of a constant hydraulic gradient in any vertical. It is well known that this assumption does not hold true, even approximately, where potential flow is dominating, as is often the case near the outlet section. It appears safe to assume, however, that this discrepancy does not affect the discharge [*Muskat*, 1937, pp. 303–318], nor the calculated piezometric level in the main part of an extensive aquifer. In the cases treated in the following, it would generally not involve excessive error to extend the validity over the whole length of the aquifer.

With the substitutions

$$z^2 = y \qquad (3)$$

$$\frac{\partial z}{\partial x} = \frac{1}{2\sqrt{y}} \cdot \frac{\partial y}{\partial x} \qquad (4)$$

$$\frac{\partial z}{\partial t} = \frac{1}{2\sqrt{y}} \cdot \frac{\partial y}{\partial t} \qquad (5)$$

Eq. (1) may be rewritten

$$\frac{\partial^2 y}{\partial x^2} - \frac{\alpha}{\sqrt{y}} \cdot \frac{\partial y}{\partial x} = \frac{\epsilon}{c\sqrt{y}} \cdot \frac{\partial y}{\partial t} - P \qquad (6)$$

in which

$$P = 2\epsilon \cdot p/c \qquad (7)$$

If we now make the assumption that z deviates only a small amount from a weighed mean depth D of the ground-water stream, (6) is further simplified to [*Werner*, 1953]

$$\frac{\partial^2 y}{\partial x^2} - a \cdot \frac{\partial y}{\partial x} = \frac{1}{k} \cdot \frac{\partial y}{\partial t} - P \qquad (8)$$

in which

$$a = \alpha/D \qquad (9)$$

$$k = c \cdot D/\epsilon \qquad (10)$$

the latter expression denoting the so-called viscosity factor of the ground-water stream.

By putting $\frac{\partial y}{\partial t} = 0$ in (6) and (8), we obtain the differential equations for steady flow

$$\frac{\partial^2 y}{\partial x^2} - \frac{\alpha}{\sqrt{y}} \cdot \frac{\partial y}{\partial x} = -P \qquad (6a)$$

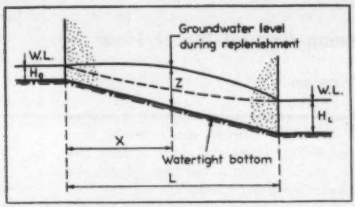

FIG. 1 – Ground-water flow between two reservoirs

and

$$\frac{\partial^2 y}{\partial x^2} - a \cdot \frac{\partial y}{\partial x} = -P \qquad (8a)$$

Both (6a) and (8a) are readily solvable by ordinary integration methods. For unsteady flow (6) is rather difficult to handle, and in this case our investigation will be based chiefly on (8) which may be explicitly solved in many cases. The approximation involved in its derivation by substituting D for z is negligible when the variations in the boundary conditions (inclusive of the replenishment from the ground surface) are small; for preliminary investigations it may also be used in other cases.

Laplace transformation—When solving (8) we shall use the Laplace transformation method (well known from the Operation Calculus) which is especially useful, observing the fact that the motive fluctuations are, as a rule, of an impulsive nature, that is, starting from rest (zero). It is not intended or necessary here to go into the pure mathematics of the method; reference may be made to representative handbooks on the subject [*Carslaw* and *Jaeger*, 1947, 1948; *Churchill, 1944*]. Our use of the method will therefore be of a more formal nature. It can also be readily verified in all cases below that the solutions obtained do satisfy the conditions of the problem.

Using here, for shortness, the integral notation

$$\oint = \frac{1}{2\pi i} \cdot \int_{-i\infty}^{+i\infty} \qquad (11)$$

the primary Laplace transforms to be used are [Churchill, pp. 295–302, 1944]

$$2\pi i \cdot \oint \frac{e^{\lambda t}}{\lambda} \cdot d\lambda = \begin{cases} =0 \text{ for } t = 0 \\ =1 \text{ for } t > 0 \end{cases} \qquad (12)$$

$$2\pi i \cdot \oint \frac{e^{\lambda t}}{\lambda^2} \cdot d\lambda = \begin{cases} =0 \text{ for } t = 0 \\ =t \text{ for } t > 0 \end{cases} \qquad (13)$$

Assume now that (8) and the initial and boundary values of a certain problem suggest a solution of the form (see, for instance, Case I.3 below).

$$y = \oint \frac{\Phi(x, \lambda)}{\Psi(L, \lambda)} \, d\lambda \qquad (14)$$

This function may be evaluated by means of the calculus of residues [*Churchill*, 1944, pp. 128–147]. According to Cauchy's Theorem it is equal to $(2\pi i)$ times the sum of the residues at the poles of its integrand. The poles are determined by

$$\Psi(L, \lambda_n) = 0 \qquad (15)$$

and (14) becomes

$$y = 2\pi i \cdot \sum \frac{\Phi(x, \lambda_n)}{\Psi^1(L, \lambda_n)} \qquad (16)$$

in which the derivative of the integrand is with respect to λ.

This formal procedure is applicable to all problems of unsteady flow in the following, which refer to aquifers of finite length.

Original Base Flow

The original base flow is defined as the steady flow existing when the condition of no replenishment from the ground surface has prevailed for a very long time. We have to solve (6a), which for $P = 0$, and after some transformations, reads

$$\frac{\partial}{\partial x}\left[z \cdot \left(\alpha - \frac{\partial z}{\partial x}\right)\right] = 0 \qquad (17)$$

Integrating once, we obtain

$$\frac{\partial z}{\partial x} = \alpha - \frac{q}{c \cdot z} = \alpha - \frac{r}{z} \qquad (18)$$

which is identical with (2) and, in fact, constitutes a condition of continuity, implying that the discharge shall have a constant value along the whole aquifer.

Aquifer of Type I (Case I.1)—The boundary conditions in this case may be written

$$z = H_0 \qquad \text{at } x = 0 \qquad (I.1.1)$$

$$z = H_L \qquad \text{at } x = L \qquad (I.1.2)$$

If we now apply the approximate (8a) with $P = 0$, we have the solution

$$z^2 = H_0^2 + (H_L^2 - H_0^2) \cdot f(ax) \qquad (I.1.3)$$

in which

$$f(ax) = \frac{e^{ax} - 1}{e^{aL} - 1} \qquad (I.1.4)$$

Eq. (I.1.3) is explicit in z and rather easy to handle. For its further application it is therefore worth while investigating its accuracy. Take, for instance, an aquifer with the following data (Example 1): $L = 1{,}000\ m$, $H_0 = 4\ m$, $H_L = 6$ m, $D \sim 4.9$ m, $\alpha = 0.006$, $\alpha \cdot L = 6$, $aL \sim 1.23$.

Combining (2) and (I.1.3), we obtain the condition of continuity for q, as follows

$$q_x = c \cdot \alpha \cdot \left[z - \frac{H_L^2 - H_0^2}{2D} \cdot \frac{e^{ax}}{e^{aL} - 1} \right] \qquad \text{(I.1.5)}$$

Introducing the above data in this expression, we find a maximum deviation from a constant value of about one per cent, which is an entirely satisfactory agreement. Subject to such a check of the continuity giving a satisfactory result, (I.1.3) may be regarded as describing the piezometric water level for the original base flow in the case under consideration.

It may be noted that for $a = 0$, that is, a horizontal bottom, (I.1.3) becomes

$$z^2 = H_0^2 + (H_L^2 - H_0^2) \cdot \frac{x}{L} \qquad \text{(I.1.6)}$$

Aquifer of Type II (Case II.1)—Assuming that no water enters the aquifer at $x = 0$, the base flow is nil. The boundary conditions are

$$\frac{\partial z}{\partial x} = \alpha \qquad \text{for all } x \qquad \text{(II.1.1)}$$

$$z = H_L \qquad \text{at } x = L \qquad \text{(II.1.2)}$$

It is easily verified that these conditions are satisfied by the simple expression

$$z = H_L - \alpha \cdot (L - x) \qquad \text{(II.1.3)}$$

which also satisfies (6a) and therefore is an approximate solution of (8a), and may be taken as the piezometric level for the original base flow in Case II.

Average Base Flow

Let us assume that a constant replenishment, corresponding to $P = P_m$, has been going on over the whole length of the aquifer, and for a long time so that steady flow prevails. In nature this condition is equivalent to the long-time average flow, around which unsteady influences oscillate.

Aquifer of Type I (Case I.2)—The boundary conditions are the same as in Case (I.1), namely

$$z = H_0 \qquad \text{at } x = 0 \qquad \text{(I.2.1)}$$

$$z = H_L \qquad \text{at } x = L \qquad \text{(I.2.2)}$$

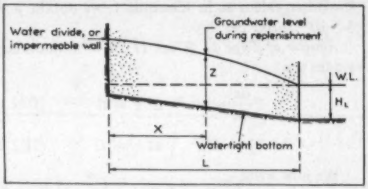

FIG. 2 – Ground-water flow between a water divide and a reservoir

Applying (8a), with $P = P_m$, we readily obtain an explicit solution, as follows

$$z^2 = G_1(ax) = z_1^2 + \frac{P_m}{a} \cdot F_1(ax) \qquad \text{(I.2.3)}$$

in which z_1 is the piezometric level for the original base flow, and in which

$$F_1(ax) = x - L \cdot f(ax) \qquad \text{(I.2.4)}$$

Eq. (I.2.3) is explicit in z, and may be taken as representing the piezometric level for the average base flow of Type I.

For $a = 0$, (I.2.3) is reduced to

$$z^2 = G_1(0x) = H_0^2 + (H_L^2 - H_0^2) \cdot \frac{x}{L} + \frac{P_m}{2} \cdot x \cdot (L - x) \qquad \text{(I.2.5)}$$

Changing here the origin to the midpoint of the aquifer, putting $H_0 = H_L$, and replacing $L/2$ by L, we obtain the well-known formula

$$z^2 = H_L^2 + \frac{P_m}{2} \cdot (L^2 - x^2) \qquad \text{(I.2.6)}$$

Compare (II.2.5) below.

In hydrologic investigations the question may arise as to the magnitude of the steady replenishment for which no water flows out of the upper reservoir. According to (2) we then have the condition $\frac{\partial z}{\partial x} = \alpha$ for $x = 0$, and by differentiation of (I.2.3) we obtain after some transformations

$$p = \frac{c}{2\epsilon} \cdot \alpha^2 \cdot \frac{e^{a_m L} - 1}{e^{a_0 L} - 1} \cdot \frac{2H_0 \cdot D_0 \cdot (e^{a_0 L} - 1) - (H_L^2 - H_0^2)}{D_m \cdot D_0 \cdot (e^{a_m L} - 1 - a_m \cdot L)} \qquad \text{(I.2.7)}$$

in which D_0 refers to the base flow and D_m to the replenishment. Assuming now (Example 2), an aquifer with $\epsilon = 0.3$, $c = 10^{-4}\ m/s$, $D_m = 5.2$ and

the other values as in Example 1, we obtain $p \sim 1.3 \cdot 10^{-3}$ meter per day.

Aquifer of Type II (Case II.2)—The boundary values are

$$\frac{\partial z}{\partial x} = \alpha \qquad \text{at } x = 0 \qquad \text{(II.2.1)}$$

$$z = H_L \qquad \text{at } x = L \qquad \text{(II.2.2)}$$

We now write

$$z^2 = z_2^2 + \frac{P_m}{a} \cdot F_2(ax) = G_2(ax) \qquad \text{(II.2.3)}$$

in which z_2 is the piezometric level for the orignal base flow, and in which

$$F_2(ax) = x - L + \frac{1}{a} \cdot (e^{aL} - e^{ax}) \qquad \text{(II.2.4)}$$

It may be verified by substitution that the second term in (II.2.3) satisfies (8a). As stated previously, the first term is a sufficiently close solution of (8a). Consequently, the expression (II.2.3) may be considered as representing the piezometric level for the average base flow in Case II.

For $a = 0$, (II.2.3) is reduced to

$$z^2 = H_L^2 + \frac{P_m}{2} \cdot (L^2 - x^2) = G_2(0x) \qquad \text{(II.2.5)}$$

which, in view of the valid boundary conditions, is identical with (I.2.6).

In current literature it is commonly assumed that the second term on the left hand side of (6) may be neglected. In effect, this is equivalent to putting $\alpha = a = 0$, which, however, may not be adequate in many cases. We shall elucidate the matter on a ground-water stream of Type II, with the following data (Example 3):

$L = 1000\ m$, $H_L = 6\ m$, $\epsilon = 0.3$, $c = 10^{-4}\ m/s$, $\alpha = 0.003$, $D \sim 7.5\ m$, $a = 0.0004$, $aL = 0.4$, $P_m = 10^{-4}$, corresponding to $p \sim 1.4 \cdot 10^{-3}\ m$/day.

Now, for the water depth at $x = 0$ (the impermeable wall, or water divide), we obtain: for a sloping bottom, according to (II.2.3)

$$z = \sqrt{(H_L - \alpha L)^2 + \frac{P_m}{a^2} \cdot (e^{aL} - 1 - aL)} \qquad \text{(II.2.6)}$$

and for a horizontal bottom, according to (II.2.5)

$$z = \sqrt{H_L^2 + \frac{P_m}{2} \cdot L^2} \qquad \text{(II.2.7)}$$

Introducing in these formulas the values given above for the ground-water stream, we obtain the water depth above the sole, namely, $z = 8.15\ m$ from (II.2.6) and $9.27\ m$ from (II.2.7). The difference amounts in this case to some 15 pct, which, although not excessive, may not be considered negligible.

UNSTEADY FLOW—AQUIFER OF TYPE I

Case I.3—Sudden change in tail-water level—Assume that in Case I.2 the tail-water level is suddenly changed a certain amount h, the numerical value of which may be negative or positive, according as the water level is lowered or raised. The initial and boundary conditions may be written

$$z^2 = G_1(ax) \qquad \text{at } t = 0 \qquad \text{(I.3.1)}$$

$$z = H_0 \qquad \text{at } x = 0 \qquad \text{(I.3.2)}$$

$$z = H_L + h \qquad \text{at } x = L \qquad \text{(I.3.3)}$$

As we now have to deal with unsteady flow, (8) applies with $P = P_m$. Observing the value of the integral (12), it is seen that the initial and boundary conditions suggest a solution of the form

$$z^2 = G_1(ax) + (h^2 + 2H_L h) \cdot e^{-a(L-x)/2} \cdot \oint \frac{\sinh \beta x}{\sinh \beta L} \cdot \frac{e^{\lambda t}}{\lambda} \cdot d\lambda \qquad \text{(I.3.4)}$$

This also satisfies (8), with $P = P_m$, provided

$$\frac{\lambda}{k} = \beta^2 - \frac{a^2}{4} \qquad \text{(I.3.5)}$$

The poles of the integrand in (I.3.4) are at

$$\lambda = 0 \qquad \beta = \frac{a}{2}$$

and

$$\lambda = -w \qquad \beta = \frac{in\pi}{L}$$

in which, according to (I.3.5)

$$w = \frac{k}{L^2} \cdot \kappa = \frac{k}{L^2} \cdot \left[\left(\frac{aL}{2}\right)^2 + (n\pi)^2\right] \qquad \text{(I.3.6)}$$

By Cauchy's theorem, (16), the residues of (I.3.4) may be written

$$\frac{\sinh \beta x \cdot e^{\lambda t}}{\sinh \beta L + L \cdot \lambda \cdot \cosh \beta L \cdot \dfrac{\partial \beta}{\partial \lambda}}$$

We thus obtain after some transformations

$$z^2 = G_1(ax) + (h^2 + 2H_L h) \cdot [f(ax) - 2 \cdot T_1(xt)] \qquad \text{(I.3.7)}$$

in which

$$T_1(xt) = e^{-a(L-x)/2} \cdot \sum_{n=1}^{\infty} (-1)^{n+1} \cdot \frac{n\pi}{\kappa} \cdot \sin\frac{n\pi x}{L} \cdot e^{-wt} \quad \text{(I.3.8)}$$

By substitution it is easily found that (I.3.7) satisfies the differential equation as well as the boundary condition of the problem. Further, by expanding the function $e^{-ax/2}f(x)$ into a Fourier sine series [*Churchill*, 1941, pp. 53–94], it may be verified that for $t = 0$ (I.3.7) is reduced to $z^2 = G_1(ax)$, as it should according to the prescribed initial condition.

Eq. (I.3.7) is the sum of a transient part and a steady-state solution. The latter, which corresponds to the steady flow obtained after a considerable (theoretically infinite) time has elapsed, is

$$z^2 = H_0^2 + [(H_L + h)^2 - H_0^2] \cdot f(ax) + \frac{P_m}{a} \cdot F_1(ax) \quad \text{(I.3.9)}$$

which, of course, has the same general appearance as (I.2.3).

For $a = 0$ we obtain from (I.3.7)

$$z^2 = G_1(0x) + (h^2 + 2H_L h) \cdot \left\{\frac{x}{L} - 2 \cdot \sum_{n=1}^{\infty} \frac{(-1)^{n+1}}{n\pi} \cdot \sin\frac{n\pi x}{L} e^{-w_0 \cdot t}\right\} \quad \text{(I.3.10)}$$

in which

$$w_0 = k \cdot \left(\frac{n\pi}{L}\right)^2 \quad \text{(I.3.11)}$$

The initial condition ($t = 0$) is here $z^2 = G_1(0x)$, and the final steady flow ($t = \infty$) is represented by

$$z^2 = H_0^2 + [(H_L + h)^2 - H_0^2] \cdot \frac{x}{L} + \frac{P_m}{2} \cdot x \cdot (L - x) \quad \text{(I.3.12)}$$

as it should be; compare (I.2.5).

It may be mentioned that a change in the head-water level can be treated similarly.

Case I.4—Sudden Change in replenishment—Assume that the replenishment is suddenly changed a certain amount corresponding to P_1, the numerical value of which may be negative or positive, according as the change is a draft or a supply. We have to solve (8) under the following initial and boundary conditions:—

$$z^2 = G_1(ax) \qquad \text{at } t = 0 \quad \text{(I.4.1)}$$

$$P = P_m + P_1 \qquad \text{at } t > 0 \quad \text{(I.4.2)}$$

$$z = H_0 \qquad \text{at } x = 0 \quad \text{(I.4.3)}$$

$$z = H_L \qquad \text{at } x = L \quad \text{(I.4.4)}$$

The conditions suggest a function

$$z^2 = G_1(ax) + k \cdot P_1 \cdot \oint \Pi(x) \cdot \frac{e^{\lambda t}}{\lambda^2} \cdot d\lambda \quad \text{(I.4.5)}$$

in which, with β given by (I.3.5)

$$\Pi(x) = 1 - \frac{e^{-a(L-x)/2} \cdot \sinh \beta x + e^{ax/2} \cdot \sinh \beta(L - x)}{\sinh \beta L} \quad \text{(I.4.6)}$$

Applying Cauchy's theorem, we obtain

$$z^2 = G_1(ax) + \frac{P_1}{a} \cdot \left\{F_1(ax) - 2 \cdot a \cdot L^2 \cdot e^{ax/2} \cdot \sum_{n=1}^{\infty} A_n \cdot \sin\frac{n\pi x}{L} \cdot e^{-wt}\right\} \quad \text{(I.4.7)}$$

in which

$$A_n = \frac{n\pi}{\kappa^2} \cdot (1 - e^{-aL/2} \cdot \cos n\pi) \quad \text{(I.4.8)}$$

Proceeding as in Case (I.3) it may be verified that (I.4.7) does satisfy all the conditions of the problem under consideration. The initial condition, at $t = 0$, is $z^2 = G_1(ax)$, and the final steady flow is represented by

$$z^2 = z_1^2 + \frac{P_m + P_1}{a} \cdot F_1(ax) \quad \text{(I.4.9)}$$

as compared with (I.2.3).

Putting $a = 0$ in (I.4.7), we obtain

$$z^2 = G_1(0x) + \frac{P_1}{2} \cdot \left\{x \cdot (L - x) - \frac{8L^2}{\pi^3} \cdot \sum_{n=0}^{\infty} \frac{1}{(2n+1)^3} \cdot \sin \mu_1 x \cdot e^{-k\mu_1^2 t}\right\} \quad \text{(I.4.10)}$$

in which

$$\mu_1 = (2n + 1) \cdot \frac{\pi}{L} \quad \text{(I.4.11)}$$

Changing here, as in (I.2.5), the origin to the midpoint of the aquifer, putting $H_0 = H_L$ and replacing $L/2$ by L, we obtain

$$z^2 = H_L^2 + \frac{P_m}{2} \cdot (L^2 - x^2) + \frac{P_1}{2} \cdot \left\{L^2 - x^2 - \frac{32}{\pi^3} \cdot L^2 \cdot \sum_{n=0}^{\infty} \frac{(-1)^n}{(2n+1)^3} \cdot \cos \mu_2 x \cdot e^{-k\mu_2^2 t}\right\} \quad \text{(I.4.12)}$$

in which

$$\mu_2 = (2n + 1) \cdot \frac{\pi}{2L} \qquad \text{(I.4.13)}$$

It is worth noting that the solutions obtained are additive, and that they are discontinuous (zero) at $t = 0$. In view of this it is possible to use (I.4.7) also for investigating the effect of a single square pulse, say with the duration t_0. This is effected by applying a charge at $t = 0$, and then at $t = t_0$ applying a draft of the same intensity, both the charge and the draft calculated according to (I.4.7). In the same manner we can form the solution for a succession of square pulses having any prescribed phases and amplitudes.

In principle, the method of superposition indicated here is applicable to all similar problems in the paper.

Case I.5—Uniformly increasing replenishment—Eq. (8) applies, and the initial and boundary values are

$$z^2 = G_1(ax) \qquad \text{at } t = 0 \qquad \text{(I.5.1)}$$

$$P = P_m + P_1 \cdot t \qquad \text{at } t > 0 \qquad \text{(I.5.2)}$$

$$z = H_0 \qquad \text{at } x = 0 \qquad \text{(I.5.3)}$$

$$z = H_L \qquad \text{at } x = L \qquad \text{(I.5.4)}$$

The value of integral (13) suggest the solution

$$z^2 = G_1(ax) + k \cdot P_1 \cdot \oint \Pi(x) \cdot \frac{e^{\lambda t}}{\lambda^2} \cdot d\lambda \qquad \text{(I.5.5)}$$

which, in turn, when compared with (I.4.5), indicates a direct integration of the latter formula. We thereby obtain

$$z^2 = G_1(ax) + \frac{P_1}{a} \cdot \left\{ t \cdot F_1(ax) - 2 \cdot a \cdot L^2 \cdot e^{ax/2} \cdot \sum_{n=1}^{\infty} \frac{A_n}{w} \cdot \sin \frac{n\pi x}{L} \cdot (1 - e^{-wt}) \right\} \qquad \text{(I.5.6)}$$

By substitution this expression is found to satisfy the initial and boundary conditions as well as (8), and therefore constitutes the solution of the problem. The solution is in itself of rather limited value, but in combinations it is very useful. Take, for instance, the case that the replenishment is uniformly increasing from $t = 0$ up to the time t_0 and thereafter remains constant. The effect of this is obtained by a uniformly increasing charge acting from $t = 0$ and a superimposed draft of the same intensity set in at $t = t_0$, both the charge and the draft represented by (I.5.6).

Likewise, it is possible to obtain the effect of a replenishment represented by a rectified or non-rectified fullwave of triangular or trapezoidal form; and so on. Combinations with Case (I.4) may also be useful. It may be mentioned in this connection that problems of this nature, involving periodic variations, may be solved by direct application of Laplace transforms, but the resulting formulas are generally so complicated as to make them rather inconvenient for practical use.

Unsteady Flow—Aquifer of Type II

Case II.3—Sudden change in tail-water level—This case corresponds to (I.3), and we write the initial and boundary values as follows

$$z^2 = G_2(ax) \qquad \text{at } t = 0 \qquad \text{(II.3.1)}$$

$$\frac{\partial z}{\partial x} = \alpha \qquad \text{at } x = 0 \qquad \text{(II.3.2)}$$

$$z = H_L + h \qquad \text{at } x = L \qquad \text{(II.3.3)}$$

The differential equation (8) applies, and the conditions suggest a solution

$$z^2 = G_2(ax) + (h^2 + 2H_L h) \cdot e^{-a(L-x)/2} \oint R(x) \cdot \frac{e^{\lambda t}}{\lambda} \cdot d\lambda \qquad \text{(II.3.4)}$$

in which

$$R(x) = \frac{a/2 \cdot \sinh \beta x - \beta \cdot \cosh \beta x}{a/2 \cdot \sinh \beta L - \beta \cdot \cosh \beta L} \qquad \text{(II.3.5)}$$

and in which β is given by (I.3.5).

If τ_n denote the roots of the equation

$$\tau_n \cdot \cot \tau_n = \frac{aL}{2} \qquad \text{(II.3.6)}$$

then the poles of the integrand in (II.3.4) are at

$$\lambda = 0 \qquad \beta = a/2$$

and

$$\lambda = -\rho \qquad \beta = i\tau_n/L$$

in which, according to (I.3.5),

$$\rho = \frac{k}{L^2} \cdot \sigma = \frac{k}{L^2} \cdot \left[\left(\frac{aL}{2} \right)^2 + \tau_n^2 \right] \qquad \text{(II.3.7)}$$

By Cauchy's theorem we now obtain

$$z^2 = G_2(ax) + (h^2 + 2H_L h) \cdot [1 - 2 \cdot T_2(xt)] \qquad \text{(II.3.8)}$$

in which

$$T_2(xt) = e^{-a(L-x)/2} \cdot \sum_{n=0}^{\infty} B_n \cdot \sin \tau_n \left(1 - \frac{x}{L}\right) \cdot e^{-\rho t} \quad \text{(II.3.9)}$$

with

$$B_n = \frac{\tau_n^3}{\sigma} \cdot \frac{1}{\left(\sigma - \frac{aL}{2}\right) \sin^2 \tau_n} \quad \text{(II.3.10)}$$

The roots of (II.3.6) may be taken from available tables [*Carslaw* and *Jaeger*, 1948, p. 378)].

It is worth noting that for $a = 0$ we have $\tau_n = (2n + 1).\pi/2$, and (II.3.8) is then simplified to

$$z^2 = G_2(0x) + (h^2 + 2 \cdot H_L \cdot h) \cdot \left\{1 - \frac{4}{\pi} \cdot \sum_{n=0}^{\infty} \frac{(-1)^n}{2n+1} \cdot \cos \mu_2 x \cdot e^{-k \cdot \mu_2^2 \cdot t}\right\} \quad \text{(II.3.11)}$$

in which μ_2 is given by (I.4.13). For $t = 0$, (II.3.11) is reduced to the initial condition $z^2 = G_2(0x)$, and for the final steady flow ($t = \infty$) we obtain

$$z^2 = (H_L + h)^2 + \frac{P_m}{2} \cdot (L^2 - x^2) \quad \text{(II.3.12)}$$

as it should be; compare (I.2.6) and (II.2.5)

Case II.4—Sudden change in replenishment—Initial and boundary conditions

$$z^2 = G_2(ax) \qquad \text{at } t = 0 \quad \text{(II.4.1)}$$

$$P = P_m + P_1 \qquad \text{at } t > 0 \quad \text{(II.4.2)}$$

$$\frac{\partial z}{\partial x} = \alpha \qquad \text{at } x = 0 \quad \text{(II.4.3)}$$

$$z = H_L \qquad \text{at } x = L \quad \text{(II.4.4)}$$

For solving (8) with the above conditions we write

$$z^2 = G_2(ax) + k \cdot P_1 \cdot \oint [1 - e^{-(a/2).(L-x)} \cdot R(x)] \cdot \frac{e^{\lambda \tau}}{\lambda^2} \cdot d\lambda \quad \text{(II.4.5)}$$

Applying Cauchy's theorem

$$z^2 = G_2(ax) + \frac{P_1}{a} \cdot [F_2(ax) - 2 \cdot a \cdot L^2 \cdot T_3(xt)] \quad \text{(II.4.6)}$$

in which

$$T_3(xt) = e^{-(a/2).(L-x)} \cdot \sum_{n=0}^{\infty} \frac{B_n}{\sigma} \cdot \sin \tau_n \left(1 - \frac{x}{L}\right) \cdot e^{-\rho t} \quad \text{(II.4.7)}$$

Here again τ_n are the roots of (II.3.6), B_n is given by (II.3.10,) and σ and ρ are given by (II.3.7).

For $a = 0$ we have again $\tau_n = (2n + 1) \cdot \frac{\pi}{2}$, and (II.4.6) becomes identical with (I.4.12), namely

$$z^2 = G_2(0x) + \frac{P_1}{2} \cdot \left\{L^2 - x^2 - \frac{32}{\pi^3} \cdot L^2 \cdot \sum_{n=0}^{\infty} \frac{(-1)^n}{(2n+1)^3} \cdot \cos \mu_2 x \cdot e^{-k \cdot \mu_2^2 \cdot t}\right\} \quad \text{(II.4.8)}$$

which for $t = 0$ reduces to the inital condition $z^2 = G_2(0x)$, and for $t = \infty$ gives

$$z^2 = H_L^2 + \frac{P_m + P_1}{2} \cdot (L^2 - x^2) \quad \text{(II.4.9)}$$

as compared with (II.2.5).

Case II.5—Uniformly changing replenishment—The initial and boundary conditons are the same as in (I.5), except that (I.5.1) is replaced by

$$z^2 = G_2(ax) \qquad \text{at } t = 0 \quad \text{(II.5.1)}$$

and (I.5.3) is replaced by

$$\frac{\partial z}{\partial x} = \alpha \qquad \text{at } x = 0 \quad \text{(II.5.2)}$$

Proceeding as in (I.5), we write

$$z^2 = G_2(ax) + k \cdot P_1 \cdot \oint \left[1 - e^{-a(L-x)/2} \cdot R(x) \cdot \frac{e^{\lambda t}}{\lambda^2} \cdot d\lambda \quad \text{(II.5.3)}\right.$$

from which

$$z^2 = G_2(ax) + \frac{P_1}{a} \cdot \{t \cdot F_2(ax) - 2 \cdot a \cdot L^2 \cdot V(xt)\} \quad \text{(II.5.4)}$$

with

$$V(xt) = e^{-a(L-x)/2} \cdot \sum_{n=0}^{\infty} \frac{B_n}{\sigma \cdot \rho} \cdot \sin \tau_n \left(1 - \frac{x}{L}\right) \cdot (1 - e^{-\rho t}) \quad \text{(II.5.5)}$$

in which B_n, σ, ρ and τ_n are as given heretofore.

Concluding remarks—The main objects of the paper are two, first to provide means of investigating the effect of a moderately sloping bottom on the

piezometric ground-water level, and second to indicate a method of solving problems of non-steady ground-water flow.

By an example it is shown that the effect of a sloping bottom may not be excessive, nor may it be taken as negligible. The question should be investigated in each separate case.

The formulas for unsteady flow are of value as they clearly show the general behavior of ground-water streams under unsteady conditions. Such conditions are frequent and important; they may be caused by artificial raising or lowering of a lake, by daily or long-term water regulation of a river course, by spreading operations in artificial infiltration, etc.

It may be observed that the infinite series involved in the formulas for unsteady flow are, as a rule, rapidly convergent.

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Appendix I

The following general notation is used in the paper; supplementary symbols and index notations are given in the text.

x	coordinate of length
L	length of aquifer
z	piezometric ground-water level
H_0	head-water level
H_L	tail-water level
D	weighted mean depth of ground-water stream
α	slope of bottom of aquifer
q	discharge of ground-water stream
p	rate of replenishment
t	time
c	Darcy's transmission constant
ϵ	effective pore space, as a decimal fraction
k	cD/ϵ, viscosity factor
a	α/D
P	$2\epsilon \cdot p/c$
m, n	integers 0, 1, 2, 3 $\cdots$
i	$\sqrt{-1}$ = unit of imaginary numbers
e	base of natural logarithms
λ	independent variable of Laplace transforms
κ	$(aL/2)^2 + (n\pi)^2$
w	$(k/L^2) \cdot \kappa$
μ_1	$(2n + 1) \cdot \pi/L$
μ_2	$(2n + 1) \cdot \pi/2L$
τ_n	roots of (II.3.6)
σ	$(aL/2)^2 + \tau_n^2$
ρ	$(k/L^2) \cdot \sigma$

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The Statistical Treatment of Flood Flows

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Abstract—The estimation of return periods of floods is considered from the point of view of mathematical statistics. This requires, essentially, the estimation of the tail of a probability distribution from a sample of values which is usually not dense in this tail. The error in the estimation of a flood corresponding to a given probability arises from two sources: (1) the uncertainty as to the mathematical form of the distribution; (2) the uncertainty arising from the statistical errors of estimation of the parameters of the distribution which occur because of the finiteness of the length of record. These errors are illustrated on a numerical example by fitting a log-normal distribution and a type III distribution to fifty annual values of extreme monthly flow of the River Murray.

When designing a dam it is necessary to be able to form some estimate of the probability of large flows which might overtax the dam. If the variable taken to measure the flood is, for example, the largest monthly flow in each calendar year, this quantity will have a probability distribution whose upper tail must be estimated. If X is the largest monthly flood flow in each year we suppose it has a probability distribution $f(x)$ such that the probability that X lies in the interval $(x, x + dx)$ is $f(x)\,dx$. We then want to estimate the probability

$$P = \int_{x_0}^{\infty} f(x)\,dx \qquad (1)$$

of the maximum monthly flow in any year being greater than x_0. It is conventional to speak of the 'hundred-year' and 'thousand-year' floods as those for which x_0 is such that $P = 0.01$ and $P = 0.001$. This implies that if T is the number of years before the next flood in excess of x_0 occurs then T is a random variable whose mean value is P^{-1}. In fact the distribution of T is the geometric distribution defined by

$$\text{Prob}\,\{T = n\} = (1 - P)^{n-1}P \qquad (2)$$

As we do not know $f(x)$ we cannot calculate P as a function of x_0. We therefore have to estimate (1) from a set of observations of floods which we denote by $x_1, \cdots x_n$. It is here that much confusion of thought about the correct statistical procedure is apparent in the literature. The purpose of the present paper is to set out what appears to the author to be the most efficient procedure and to show its essential limitations. These limitations arise from the shortness of the series of observations and cannot be overcome by mathematical sleight of hand. On the other hand the shortness of the series of observations makes it necessary to use the most efficient possible statistical procedure for it is known that many statistical procedures are inefficient in the sense that they do not extract all the information in the series.

If we had, say, a million observations it would be easy, by a simple method, to obtain quite accurate estimates of the values of x_0 for which $P = 0.01$ or $P = 0.001$, but in actual fact we rarely have more than about 50. In such cases the value of x_0 for which P has such small values is usually well outside the range of the observations $x_1, \cdots x_n$. Thus we have to estimate the shape of the tail of the distribution $f(x)$ from a set of observations not lying in this tail.

The natural method of procedure is to assume that $f(x)$ has some simple form involving only a few parameters (usually two), and then use the observations to estimate these parameters. There are two sources of error in such a procedure.

In the first place the form of the distribution is not known and any distribution used must be guessed. This may have a considerable effect since the part of the distribution we are interested in is well away from the part where the observations provide some information about the shape. It is therefore easy to construct two different distributions both of which fit the observations closely but for which the tails are of quite different shape. This difficulty cannot really be surmounted, but we can try to fit several different distributions and see how the choice affects the result. It would also be desirable to use some measure of goodness of fit on the fitted distributions. Thus, splitting the range up into a number of intervals we might compare the observed and predicted frequencies by the use of the χ^2 test with $N - 1 - k$ degrees of freedom where N is the number of intervals and k the number of parameters fitted. This is asymptotically a valid test if the parameters are fitted by a method which is asymptotically most efficient (for example,

the method of maximum likelihood). The small number of observations usually available makes this test not very sensitive and what is more important, it tests the goodness of fit mainly in the part of the range where the observations are concentrated. We might also use some other test such as the ω^2 test but this is not very satisfactory when parameters have to be fitted.

The second source of error lies in the fact that the observations provide estimates of the parameters of the distribution which are themselves subject to error. Hence the method of fitting must minimize these as far as possible and must therefore be as efficient as possible. The method of maximum likelihood is usually the easiest such method to apply. In previous discussions of the statistics of flood flows, logarithmic-normal distributions have often been fitted by plotting the observations on logarithmic-normal probability paper and drawing a straight line through the points by eye. Not only is this inefficient but the method of plotting is itself subject to ambiguities. The correct method of fitting a logarithmic-normal distribution is to take the logarithms of the observations and use their observed mean and standard deviation as estimates of the distribution parameters.

The type-III distribution, which is often very suitable, must not be fitted by equating moments. This can be shown to be a most inefficient procedure and the correct method of fitting will be shown by an example later. Without a great complication of the method, we must assume that the sequence of observed values are statistically independent. Thus even if no linear or seasonal trend is present we could not use daily records since these are serially dependent.

A distribution which has been occasionally used in this problem is Gumbel's extreme value distribution. This distribution is the asymptotic form of the distribution of the largest member of a sample of n independent quantities from a distribution which satisfies certain very general conditions on the asymptotic behaviour of its tail. This asymptotic form may be attained very slowly and when applied to the largest member of a sample from a normal population requires the sample size to be at least of the order of 10^{12}. For other distributions, however, the asymptotic form may be attained more quickly.

Gumbel's distribution might be applied in two ways. One is to try to estimate those properties of the distribution $f(x)$ which determine the parameters in Gumbel's extreme value distribution. This is however equivalent to estimating the tail of $f(x)$ and is thus only a roundabout and confusing way of doing what is attempted directly in this paper. The other way in which Gumbel's distribution might be applied is to regard it as another of the wide family of distributions on $(0, \infty)$ which might be used for $f(x)$. This might be applied to, say, the largest daily flow out of each year. The objection to this is that daily flows for one year do not represent a sample of 365 independent values from a distribution since there usually exists a strong seasonal variation and moreover daily flows are not serially independent. The distribution is also awkward to fit mathematically by efficient methods. For these reasons Gumbel's distribution is not relevant to the problem considered in this paper.

To illustrate the above remarks and to draw attention to the considerable uncertainty which still remains even when the most efficient methods are used we consider a numerical example. The x_i were chosen to be the largest monthly flow, in thousand acre-feet, in each of the 50 years 1891–1940 of the River Murray at Jingellic, Victoria. These maxima usually occur in the months June to November and being well separated are unlikely to be serially correlated. A simple regression on time also indicates no significant trend. We consider what happens when we fit a logarithmic normal distribution and a type III.

Fitting of log-normal distribution—Writing $x_1, \cdots x_{50}$ for the observations and $y_1, \cdots y_{50}$ for their common logarithms we suppose that the distribution of the y_i is given by

$$f(y) = \frac{1}{\sigma(2\pi)^{\frac{1}{2}}} e^{-(y-\mu)^2/2\sigma^2} \tag{3}$$

where μ and σ are the true mean and standard deviation. Fully efficient estimators of μ and σ are then given by

$$\hat{y} = n^{-1} \sum y_i \tag{4}$$

$$s = \left\{ \frac{\sum (y_i - \hat{y})^2}{n-1} \right\}^{\frac{1}{2}} \tag{5}$$

These two quantities are independently distributed. For the 50 years 1891–1940 we get

$$\hat{y} = 2.5466, \quad \text{and} \quad s = 0.2141.$$

The values of Y which make

$$(2\pi)^{-\frac{1}{2}} \int_Y^\infty e^{-\frac{1}{2}t^2} \, dt$$

equal to 0.01 and 0.001 are 2.3263 and 3.0902 respectively. The estimates of the logarithms of the corresponding 100 and 1000 year floods are therefore 2.5466 + 2.3263 (0.2141) = 3.0447 and 2.5466 + 3.0902 (0.2141) = 3.2082, the corresponding values of x being 1108 and 1615 thousand acre feet.

We now calculate the standard errors of these estimates. Let Z_1 be the estimate of the 100 year flood. Then

$$\log_{10} Z_1 = \bar{y} + (2.3263)s.$$

If the standard errors of $\bar{y}$ and s are e_1 and e_2 we have

$$\{\text{S.E. } (\log_{10} Z_1)\}^2 = e_1^2 + (2.3263)^2 e_2^2$$

where S.E. $(\log_{10} Z_1)$ is the standard error of $\log_{10} Z_1$. Estimates of e_1 and e_2 are given by $sn^{-\frac{1}{2}}$ and $s(2n)^{-\frac{1}{2}}$. Substituting these we get S.E. $(\log_{10} Z_1)$ = 0.05828. Multiplying by 1.96 to obtain a 95 pct confidence interval we can assert that, with probability 0.95 the interval

$$\log_{10} Z_1 \pm 1.96 \text{ (S.E. } (\log_{10} Z_1))$$

will cover the true value of the 100-year flood provided that the assumption that the true distribution is log-normal is correct. (This is, of course, an approximate statement based on the approximation of the distribution of $\log_{10} Z_1$ by a normal distribution.) For the 100-year flood this gives the interval (852–1442). This assumes that $\log Z_1$ is normally distributed which is a near enough approximation, the units figure being clearly not significant. The corresponding 95 pct confidence limits for the 1000-year flood are (1163–2243). Thus we have not only made an estimate of these floods but have also constructed limits within which the true value probably lies.

It is instructive to carry out the same calculations for a 25-year period. Taking the observations for 1891–1915 we get estimates 910 and 1287 thousand acre feet for the 100-year and 1000-year floods with 95 pct confidence intervals (646–1282) and (840–1974) respectively.

The fitting of a type-III distribution—Here we have

$$f(x) = \frac{1}{a\Gamma(k)} e^{-xa^{-1}}(xa^{-1})^{k-1}\, dx \qquad (6)$$

We estimate k and a by choosing them to maximize the likelihood of the observations, or what is the same thing, by maximizing the natural logarithm of the likelihood This is $L = -n \ln \Gamma(k) - a^{-1}\sum x_i + (k-1)\sum \ln x_i - nk \ln a$, using natural logarithms. The estimators, $\hat{k}$ and $\hat{a}$, are the solutions of

$$-n\Gamma'(k)\Gamma(k)^{-1} + \sum \ln x_i - n \ln a = 0 \qquad (7)$$

$$a^{-2}\sum x_i - nka^{-1} = 0 \qquad (8)$$

From (8) we see that $\bar{x} = \hat{k}\hat{a}$ and we can solve (7) by successive approximation, choosing $\hat{k}$ first and then $\hat{a} = \bar{x}\hat{k}^{-1}$. It is useful to begin with a first approximation obtained by equating the first two moments of (6) to the observed first and second moments. This is the method of fitting by equating moments which is here simple but inefficient. In this way we get estimators $\bar{x}^2 s^{-2} = 4.189$ and $s^2\bar{x}^{-1} = 94.05$ for k and a respectively. Choosing a series of values of k around 4.189 we calculate the corresponding values of a from (8) and interpolate on k until (7) is satisfied, a graphical method being quite satisfactory.

In this way we find for the 50 years 1891–1940, $\sum \ln x_i = 293.18$ and $\hat{k} = 4.60$, $\hat{a} = 85.64$ (the values of the function $\Gamma'(k)\Gamma(k)^{-1}$ can be found in *Davis* [1933]). It is now instructive to compare the goodness of fit of this distribution with the log normal. Values of the integral of (6) can be found from Pearson's Tables of the incomplete Γ function (see Table 1).

The cell sizes were chosen to make the calculation for the log-normal curve simple. Grouping the first two and last two cells together we obtain χ^2s of 0.86 and 0.36 with one degree of freedom, for the log normal and type III respectively. Neither is significant but the latter appears to be a somewhat better fit.

From Pearson's tables of the incomplete Γ function we find the values of v_0 which make

$$\Gamma(4.6)^{-1}\int_0^{v_0} e^{-v} v^{3.6}\, dv$$

equal to 0.99 and 0.999. These are 10.990 and 14.113. Multiplying by $a = 85.64$ we get 941 and

TABLE 1 – *Goodness of fit of log-normal and type-III distributions*

Flood flow	Frequency observed	Log normal	Type III
80.2–131.2	3	1.08	1.39
131.3–214.9	5	6.80	6.07
215.0–351.9	15	17.06	15.66
352.0–576.3	20	17.06	18.91
576.4–943.5	6	6.80	7.18
943.6 or more	1	1.08	0.49

1209 thousand acre feet for the 100-year and 1000-year floods. We must now estimate their standard errors.

Let X_0 be the 100-year (say) flood estimate from estimated values k and a. Then

$$\delta X_0 = \frac{\partial x_0}{\partial k}\,\delta k + \frac{\partial x_0}{\partial a}\,\delta a$$

so that

$$\{\text{S.E. } (x_0)\}^2 = \left(\frac{\partial x_0}{\partial k}\right)^2 \text{var } (\hat{k})$$

$$+ 2\left(\frac{\partial x_0}{\partial k}\right)\left(\frac{\partial x_0}{\partial a}\right)\text{Cov } (\hat{k}, \hat{a}) + \left(\frac{\partial x_0}{\partial a}\right)^2 \text{var } (\hat{a}).$$

Here var $(\hat{k})$ and var $(\hat{a})$ are the variances of $\hat{k}$ and $\hat{a}$ estimated from the data and Cov $(\hat{k}, \hat{a})$ their covariance. The easiest way to calculate $\partial x_0/\partial k$ is to calculate x_0 for two values of k on either side of $\hat{k}$ and estimate the differential coefficient from the difference. This will usually be adequate since very accurate values are not necessary. The term $\partial x_0/\partial a$ can be found at once since it is equal to v_0.

To obtain the variances and covariances of $\hat{k}$ and $\hat{a}$ we differentiate (7) and (8) again to obtain

$$\frac{\partial^2 L}{\partial k^2} = -n\{\Gamma(k)\Gamma''(k) - \Gamma'(k)^2\}\Gamma(k)^{-2} \quad (9)$$

$$\frac{\partial^2 L}{\partial k \partial a} = -na^{-1} \quad (10)$$

$$\frac{\partial^2 L}{\partial a^2} = -nka^{-2} \quad (11)$$

Then the variance-covariance matrix

$$\begin{Bmatrix} \text{Var } (\hat{k}) & \text{Cov } (\hat{k}, \hat{a}) \\ \text{Cov } (\hat{k}, \hat{a}) & \text{Var } (\hat{a}) \end{Bmatrix}$$

is the inverse of the matrix

$$\begin{Bmatrix} -\dfrac{\partial^2 L}{\partial k^2} & -\dfrac{\partial^2 L}{\partial k \partial a} \\ -\dfrac{\partial^2 L}{\partial k \partial a} & -\dfrac{\partial^2 L}{\partial a^2} \end{Bmatrix}$$

In this way we find the standard error of the estimated 100-year flood to be 88 thousand acre feet so that we can set confidence limits of 769 and 1115 thousand acre-feet. In a similar way we find a confidence interval (1163–2243) for the 1000-year flood. The results using various methods are summarized in Table 2.

These results show how estimates may vary when the form of $f(x)$ assumed varies although both the log normal and the type III appear to fit the data very well. The widths of the confidence intervals show, on the other hand, the uncertainty which arises from the shortness of the series even if the exact form of the distribution were known.

It is perhaps worth drawing attention to a somewhat peculiar type of statistical inference which can be drawn in certain circumstances. Suppose $x_1, \cdots x_n$ is a sample from an unknown continuous distribution and suppose M_n is the largest of these values. Then we can assert that

$$\text{Prob } \{x_{n+1} > M_n\} = (n+1)^{-1}$$

where x_{n+1} is the value for some other given year. This probability refers not to the single distribution of x_{n+1} but to the joint distribution of $\{x_1, \cdots x_{n+1}\}$. This does not enable us to estimate a $(n+1)$-year flood for it only makes a probability statement about a single year outside the sample. To illustrate, from the 50 years of data for the River Murray at Jingellic we find $M = 1195$ thousand acre feet. We could therefore assert that

$$\text{Prob } \{x > 1195\} = 0.02$$

where x is the maximum flood in 1957, say, the probability reference distribution being the joint distribution of x and the 50 observed values.

We cannot obtain in this way statements involving probabilities less than $(n+1)^{-1}$. However it is a curious fact that if the true distribution is a logarithmic normal one we can extend this idea to make a similar exact probability statement about x corresponding to any level of probability. For suppose $x_1, \cdots x_n$ is a sample from a log-normal distribution and let $y_1, \cdots y_n$ be their logarithms, and thus a sample from a normal dis-

TABLE 2 – *Estimates and confidence intervals for 100- and 1000-year floods*

Item	100-year floods		1000-year floods	
	Estimated flood	95 pct confidence interval	Estimated flood	95 pct confidence interval
Log - normal, 50 years....	1108	852–1442	1615	1163–2243
Log - normal, 25 years....	910	646–1282	1287	840–1974
Type III, 50 years.....	941	768–1114	1209	956–1462

tribution. Let y_{n+1} be distributed in the same normal distribution which we suppose has an unknown standard deviation σ. Then $y_{n+1} - \bar{y}$ is distributed normally with mean zero and standard deviation $\sigma[(n+1)/n]^{\frac{1}{2}}$ of which we have an independently distributed estimator s

$$[(n+1)/n]^{\frac{1}{2}}.$$

It follows that

$$\frac{y_{n+1} - \bar{y}}{s}\left(\frac{n}{n+1}\right)^{\frac{1}{2}}$$

is distributed in Students t distribution with $n-1$ degrees of freedom. For the 50 years data we have

$$\bar{y} = 2.5466, s = 0.2141$$

and taking the one per cent level for t we can say that

$$y_{n+1} > 2.5466 + 0.5196$$

or $x_{n+1} > 1165$ with probability 0.01. Here again the probability refers to the joint distribution of x_{n+1} and the 50 years of observations.

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Relation of Potential Evapotranspiration to Environment and Kind of Plant

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Abstract—The purpose of this investigation was to establish relationships between potential evapotranspiration and several elements of weather, potential evapotranspiration as influenced by the surroundings and irrigation of the surroundings, and potential evapotranspiration of Kentucky bluegrass, sweet corn, and celery. High correlations were found between measured potential evapotranspiration (PE) of bluegrass and open-pan evaporation, atmometer evaporation, average temperature, solar radiation, and duration of sunshine when data were grouped into between-rain periods. When the same data were grouped into seven-day periods, relatively low correlations were obtained. Uniform surroundings, watered daily, were found to reduce measured PE of bluegrass 23.2 pct below bluegrass in non-uniform surroundings which were not watered. Measured PE exceeded evapotranspiration computed by the Thornthwaite empirical formula by 10 to 70 pct and appeared more closely associated with amount of rainfall than with mean temperature. Water use by sweet corn was found to be 22.2 pct higher than use by bluegrass. Although the surrounding area of celery was watered each day, PE was 11.0 pct greater than that of bluegrass, the surrounding area of which was not watered. When compared with PE of bluegrass which received daily irrigation of surroundings, water use by celery was 36.8 pct greater.

Introduction—Because of inconsistencies in the literature on potential evapotranspiration (PE), there is a need for reexamination of methods. In many studies no distinction has been made between evapotranspiration under natural conditions and potential evapotranspiration wherein supplemental water is applied to tanks.

During rainless periods under natural conditions, a dry surface layer forms in the soil which resists upward vapor diffusion [*Schofield*, 1950; *Hide*, 1954]. The inhibition of vapor loss by a dry soil surface was shown by *Penman* and *Schofield* [1941] who reported that in southern England evaporation from a fallow soil was less during summer than during winter and attributed the lower degree of summer evaporation to drying of the soil surface. *Veihmeyer* and *Brooks* [1954] found as the drying period increased water loss from a bare soil was reduced. They reported water losses as 0.2 inch per day, 0.5 inch for five days, 1.0 inch for seventeen days, and only 1.5 inches for forty-three days.

Mather [1953] showed that PE of grass tanks watered each day was between 24.8 pct and 42.3 pct higher than PE of tanks with constant water tables. It would thus appear that the more frequently a grass surface is watered the higher will be the apparent PE.

The objectives of the present investigation were to study PE as proposed by *Thornthwaite* [1948]: (1) in relation to several elements of weather, (2) as influenced by the surroundings and irrigation of the surroundings, and (3) of Kentucky bluegrass, sweet corn and celery.

Materials and Methods—Fifteen evapotranspirometers were installed in five units of three tanks each. *Mather's* [1951] method of installing and operating modified evapotranspirometers was followed in respect to soil type, daily water application and percolate collection, clipping Kentucky bluegrass and averaging data of triplicate tanks.

In addition, tanks were installed with both uniform and nonuniform surroundings. Two plants were grown in each of the corn and celery tanks. In 1955 the surrounding area of one bluegrass unit and the surrounding area of the celery unit were irrigated each day at the time tanks were watered. Metal cylinders which extended well above tops of plants were fitted over the evapotranspirometers to exclude water. Although soil moisture of the area around tanks was not measured, an attempt was made to apply an amount of water by irrigation approximately equal to the amount applied to tanks.

Kentucky bluegrass was established in nonuniform surroundings in evapotranspirometer Units 1 and 2 in two rows of six tanks each (Fig. 1a). A common collection pit separated the tiers and the top of the pit was covered with bare soil. A grassed area 25 by 40 ft was on one side of the installation with weather instruments projecting about 15 ft into the air. A second side was bordered by a dirt road ten feet from the installation and the other two sides by low-growing row crops.

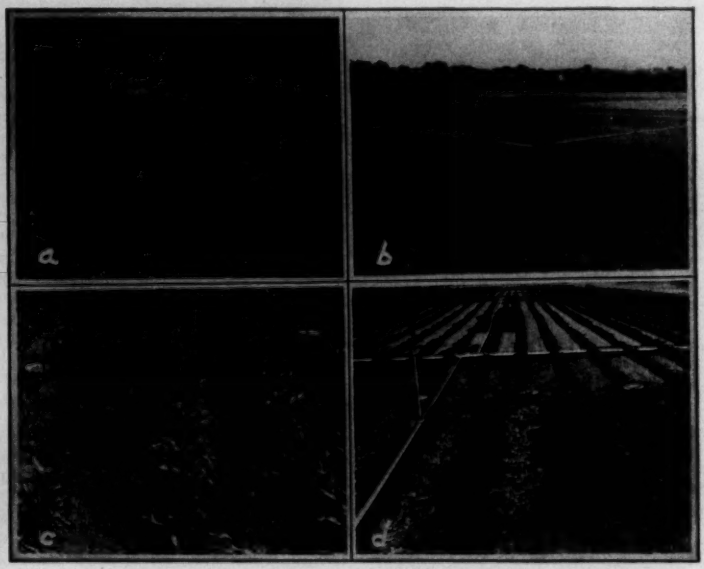

FIG. 1 – Evapotranspirometer units: (a) non-uniform surroundings, Kentucky bluegrass, Units 1 and 2; (b) uniform surroundings irrigated in 1955, Kentucky bluegrass, Unit 3; (c) uniform surroundings, sweet corn, Unit 4; (d) uniform surroundings, celery, Unit 5

Kentucky bluegrass, Unit 3, was established in a uniform field of bluegrass 140 by 150 feet and the surroundings irrigated each day in 1955 (Fig. 1b). Unit 4 was planted to sweet corn in a field of the same crop 70 by 90 feet (Fig. 1c). Celery evapotranspirometers, Unit 5, were established in a uniform field of celery 70 by 100 ft and the surroundings irrigated daily (Fig. 1d).

PE data were taken between June 1 and September 21, 1953, a period of 113 days. In 1954 data were recorded from June 6 to August 30, a period of 85 days. In 1955 data were recorded May 21 to August 11 and September 2 to 23, a total of 103 days. Heavy rains associated with hurricanes flooded tanks and shortened the 1954 and 1955 seasons.

Several elements of weather were measured. Air temperature was measured by means of a thermograph and maximum-minimum thermometers, evaporation was measured with a U. S. Weather Bureau Class-A pan and two black and two white atmometers. Solar radiation was derived indirectly by black minus white atmometer values and sunshine duration was measured by a triple register.

Relation of PE to climatic elements—The object of relating PE to climatic elements has been to utilize measurements of these elements for predicting evapotranspiration in areas where meterological data were available, but where data for measured PE were not available. Several workers have found close relationships between various climatic elements and evapotranspiration of certain crops [*Blaney*, 1952; *Comin* and *Wilson*, 1941; *Harrold*, 1955; *Penman*, 1948].

In the present study correlations between each of several climatic elements and PE of bluegrass, Unit 1 varied with method of grouping data (Table 1). By grouping data into between-rain periods it was found that open-pan evaporation, atmometer evaporation, average temperature, solar radiation, and duration of sunshine produced high correlations with PE of bluegrass, Unit 1. It was found that all but one of the coefficients of

TABLE 1 – *Correlations of measured PE (Unit 1) with several climatic elements with data grouped into between-rain periods and seven-day periods*

Climatic element	Between-rain periods			Seven-day periods		
	1953	1954	1955	1953	1954	1955
	r	r	r	r	r	r
Class-A pan evaporation	0.97	0.90	0.93	0.51	0.63	0.90
Black atmometer evaporation	0.97	0.88	0.95	0.59	0.37	0.66
Solar radiation[a]	0.99	0.94	0.92	0.39	0.24	0.67
Temperature (average)	0.96	0.94	....	0.32	0.47	....
Sunshine (hr. duration)	....	0.92	0.94	....	0.45	0.74

[a] Derived from black minus white atmometer values, corrected.

correlation resulting from these comparisons were above $r = 0.90$. However, when these same data were regrouped into arbitrary seven-day periods, most of the high correlations were lost. It should be emphasized that a high correlation does not necessarily denote that actual seasonal or per-day averages will agree. Such values are of interest in using meteorological data for hydrologic or irrigation problems.

The grouping of evapotranspiration data into arbitrary time periods of uniform duration has been a common practice. However, in a relatively early paper, *Penman* and *Schofield* [1941] cautioned that arbitrary periods should not be used as a basis for grouping evaporation data. They proposed use of a 'natural periods' concept, which in their investigation with constant water table lysimeters was defined as a period, the beginning and end of which was marked by a rise in the water table. It was pointed out that a moisture deficit which began to build up in an earlier period might erroneously be assigned to a later period if arbitrary day, week, or month groupings were used. In the current study between-rain periods were selected as being most closely related to climatic 'natural periods.' A rainfall was designated as 0.20 inch or more because it was found that percolation under an established cover of bluegrass was not greatly influenced with less water.

PE of bluegrass Unit 1 was 15.6, 3.8 and 7.3 pct greater than open-pan evaporation in 1953, 1954, and 1955 respectively (Table 2). However, in 1955 when the uniform surroundings of bluegrass Unit 3 were irrigated daily, PE was 14.8 pct less than open-pan evaporation. *Penman* [1948] established 'provisional' values of evaporation from a turf at 80 pct of open-water evaporation during May through August. He estimated that evaporation from a freshly wetted bare soil was 90 pct of that from an open water surface. *Harrold* [1955] reported that evapotranspiration from corn was 33 pct greater than pan evaporation during July and August when soil moisture was adequately supplied. In the current work, PE of corn in July and part of August 1954 was 21.2 pct greater than pan evaporation (Table 2).

It should be pointed out that *Thornthwaite* and *Holzman* [1942] and *Mather* [1954] maintain that evaporation from a large body of water is a more accurate indication of true evaporation than evaporation from a small surface. Recently, *Kohler* and others [1955] have shown empirical relationships between evaporation from pans and lakes. *Blaney* [1952] stated there was a close correlation between transpiration of plants and evaporation from a free water surface, air temperature, solar radiation and wet bulb readings, but did not present coefficients.

In the current study evaporation from a Weather Bureau Class-A pan was considerably higher than evaporation from black atmometers (Table 2). Each year two new black atmometers having the same correction coefficients and fitted with non-absorbing valves were placed in nearly the same location. *Wilson* [1940] has estimated that a loss of 264 gm of water from a standard atmometer is equal to one inch of evaporation from a standard

TABLE 2 – *Relation of computed and measured PE to evaporation, rainfall, and average air temperature*

Item	June 1 to September 21 1953	June 6 to August 30 1954	May 1 to August 11 and September 2 to 23 1955
	in/day	in/day	in/day
Computed PE[a]	0.152	0.151	0.173
Measured PE, Unit 1	0.259	0.220	0.191
Measured PE, Unit 2	....	....	0.173
Measured PE, Unit 3	....	0.214	0.155
Measured PE, Unit 4	....	0.269 (39 days)	....
Measured PE, Unit 5	....	....	0.212
Class-A pan evaporation	0.224	0.212	0.178
Black-atmometer evaporation[b]	0.127	0.135	0.119
Rainfall	0.086	0.117	0.123
Average air temperature, °F	66.4	66.2	70.8

[a] Computed by *Thornthwaite's* [1948] empirical formula.

[b] Average of two atmometers, grams/264 = inches [*Wilson*, 1940].

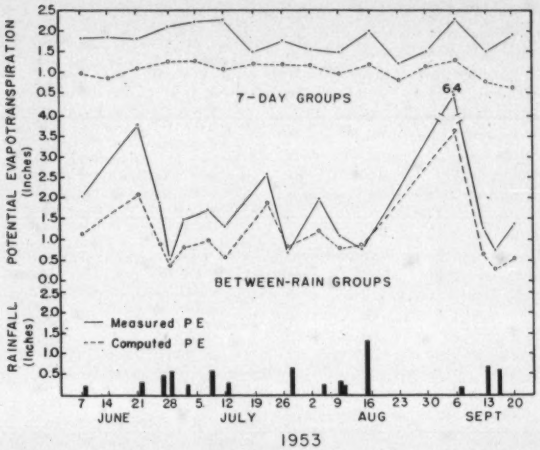

FIG. 2 – Relationship of measured PE to computed PE with data arranged in seven-day and between-rain groups

United States Weather Bureau pan. This value has been used to convert grams of water lost per atmometer to inches of evaporation. Evaporation from an open pan was 76.4, 57.0, and 49.6 pct higher than black atmometer evaporation in 1953, 1954, and 1955 respectively. Each successive year rainfall was higher, and the discrepancy between open-pan and atmometer evaporation narrowed somewhat. It would appear that the 264 gm conversion factor [*Wilson*, 1940] is too high. *McCloud* and *Dunavin* [1954] also reported poor agreement between evaporation from an open pan and from an atmometer.

Black atmometer correlation with PE of bluegrass Unit 1 was $r = 0.97$, 0.88, and 0.95 in the three years of the present study (Table 1). *Smith* [1954] reported a correlation of $r = 0.87$ between black atmometer evaporation and PE. *Comin* and *Wilson* [1941] found a close relationship between evaporation from a black atmometer and depletion of soil moisture under crops.

Relation of measured PE to PE computed by the Thornthwaite method—Good correlations of measured PE with computed PE were found only when data were grouped into between-rain periods (Table 1). With such groupings, correlation coefficients were $r = 0.97$, 0.94, and 0.97 for the three years. However, when these same data were grouped into seven-day periods, correlation coefficients dropped to $r = 0.40$, 0.43, and 0.71. Note (Table 2) that in each of the three years, actual values of measured PE were larger than actual values of computed PE. The effect of grouping data on change in correlation may be seen when between-rain and seven-day groupings are presented graphically (Fig. 2). In 1953 there were eight, seven-day groups out of a total of 16, in which the direction of change of measured PE was opposite from the change in computed PE. However, when these same data were grouped between rainfalls, measured PE and computed PE increased together and decreased together, thereby allowing good correlation. In 1954 five out of 12 seven-day groups showed opposite trends between measured and computed PE and in 1955 there were six such groups out of 14.

Measured PE exceeded computed PE by 70.4, 45.7, and 10.4 pct in 1953, 1954, and 1955 respectively (Table 2). Since computed PE is based primarily on temperature, it would appear that measured PE was strongly influenced by amount of rainfall. In 1954 rainfall was 36.0 pct higher than in the previous year and in 1955 rainfall was 5.1 pct higher than in 1954. In the first two years average air temperature was essentially the same, yet measured PE of bluegrass Unit 1 was reduced 17.7 pct the second year. Average temperature increased 4.6°F in 1955, but computed PE was

10.4 pct below measured PE. *Ramage* [1954] also found a closer relationship between measured PE and rainfall than between measured PE and temperature. By using ten years of runoff data, he found evapotranspiration to be about 16 pct above computed PE. *McCloud* and *Dunavin* [1954] reported annual measured PE of bahiagrass to be about 60 pct greater than computed PE. They found that measured values were about 77 pct higher than computed values in the summer months.

Effect of exposure and treatment of exposure on PE—In 1955 the surroundings of bluegrass Unit 3 and celery Unit 5 were irrigated daily at the time tanks were watered. The effect of daily irrigation of bluegrass Unit 3 which had a uniform exposure was to reduce PE 23.2 pct when compared with Unit 1, the exposure of which was non-uniform and not irrigated (Table 2). It has been cautioned that a uniform microclimate should be maintained throughout the exposure of evapotranspirometers [*Mather*, 1954; *Schofield*, 1950; *Thornthwaite*, 1954].

PE of three crops—Sweet corn was grown in 1954, and although only 39 days of data were available because of the August hurricane, 0.269 inch per day, the highest rate of PE in the three-year study was recorded. This was 22.2 pct higher than measured PE of bluegrass Unit 1. In the work reported here, celery Unit 5 was operated similar to bluegrass Unit 3. In spite of irrigating the surrounding area of celery each day, PE was 11.0 pct greater than bluegrass Unit 1, and 36.8 pct greater than in bluegrass Unit 3 which was treated the same as celery. Several investigators have reported that type of plant cover had little influence on evapotranspiration, [*Mather*, 1954; *Sanderson*, 1950; *Schofield*, 1950; *Thornthwaite*, 1948]. However, *Ramage* [1954] found average daily PE of Chinese cabbage, lettuce, and tomatoes to be 0.232, 0.181 and 0.272 inch, respectively, while PE of grass in the same growing periods was only 0.146, 0.106 and 0.118 inch.

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Shadow Zones, Travel Times, and Energies of Longitudinal Seismic Waves in the Presence of an Asthenosphere Low-velocity Layer

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Abstract—Theoretical computations, using the ray theory, are made of the extent of the shadow zone, travel times, and energies of longitudinal waves, assuming an asthenosphere low-velocity layer. A profile with velocity as an exponential function of the radius in each layer leads to relatively simple expressions both of distances and travel times. The shadow zone has a maximum width for a focus in the level of maximum velocity (h = 50 km in our model) and vanishes for foci about 20 km below the level of minimum velocity. Outside the shadow zone a caustic is formed with high energy concentration, beyond which the travel-time curve shows two branches, the later existing only up to a certain distance. There is much less energy arriving on the second of these branches than on the first. Other effects which may explain the arrival of energy also within the shadow zone are discussed qualitatively. Such effects include reflections from the Earth's surface and at internal discontinuities, scattering, diffraction.

Introduction—One aim of the present investigation is to take the first steps toward forming a more complete theory of the seismic-wave phenomena associated with low-velocity layers. The extent of the shadow zone, travel times, and energies are computed by the ray theory for longitudinal waves in the presence of an assumed asthenosphere low-velocity layer. It is hoped that the theoretical results presented below may be of use for comparison with observations. Discrepancies between theory and observation may call for consideration of some of the effects discussed under *Other effects* below or will require a revised velocity-depth profile.

In a series of recent papers *Gutenberg* has presented evidence for the existence of low-velocity layers in the Earth, both in the crust (lithosphere) and in the mantle (asthenosphere). Reference will especially be made to *Gutenberg* [1954], from which Figure 1 is reproduced. This figure illustrates in a qualitative way the wave paths, including channel waves, shadow zone, and travel times for a given velocity-depth profile and various depths of the focus H. In Figure 1 the Earth's curvature is neglected. In that case the wave paths are circular arcs for a linear variation of velocity with depth, which facilitates the graphical construction. In the following computations the Earth's curvature was taken into account, in which case the paths are circular arcs only provided the velocity varies with the square of the depth. Because only a small fraction of the Earth's radius is considered here, the deviation between the following computations and Figure 1 is completely negligible.

The most pronounced low-velocity layer (for P waves) is located immediately inside the outer core boundary. It is well known that this low-velocity layer gives rise to a shadow zone, diffraction phenomena and the formation of a caustic which are very similar to the corresponding phenomena in the present case. The phenomena due to the core boundary are on a much bigger scale, and results from their study may be very useful in interpreting the present small-scale phenomena due to an asthenosphere low-velocity layer.

Notation; choice of velocity profile.—The following notation will be used.

v = the velocity of P waves, km/sec
h = the depth below surface, km
r = the radius of any layer, km
i = the angle of incidence; in all cases only the angle $\leq 90°$ is given
b = the exponent of r in the velocity-depth equation
s = the epicentral distance, km or degrees
t = the travel time, min and sec
e = the energy of P waves per unit area of the Earth's surface, an arbitrary unit
E_0 = the total energy of P waves from an earthquake, the same unit as e
ϵ = a quantity proportional to e
ω = solid angle

The letters A, B, C, and the figures 0, 1, 2 (see the velocity profile in Fig. 2) will be used as subscripts in order to refer a quantity to a certain layer or

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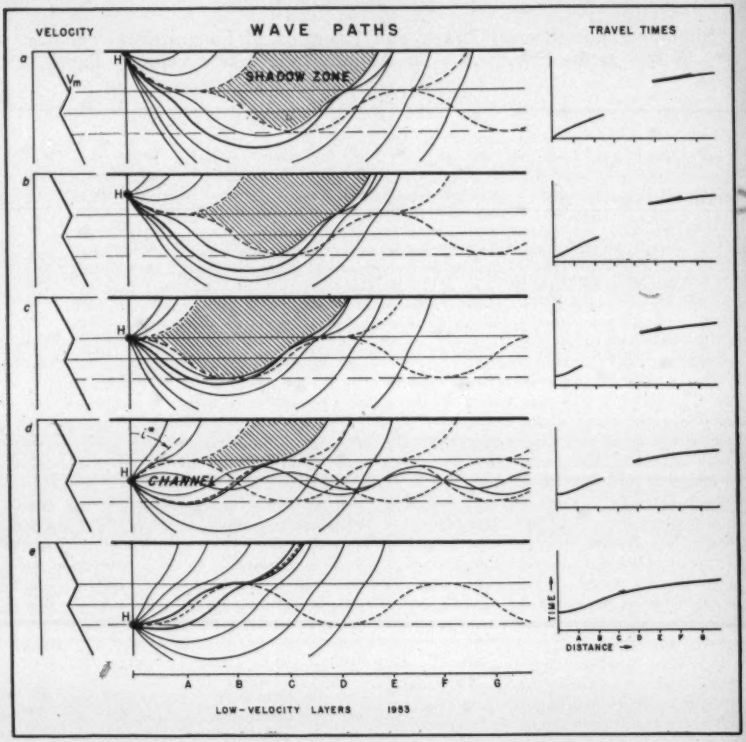

FIG. 1 – Wave paths, shadow zones, and travel times for an assumed velocity profile including a low-velocity layer; reproduced from *Gutenberg* [1954] by permission

to a certain level respectively; for example, r_0 (= 6370 km), r_1 (= 6320 km), r_2 (= 6270 km); i_0, i_1, i_2; v_0, v_1, v_2; t_A, t_B, t_C. For other depths, h is used as a subscript; for example, i_h, v_h.

A velocity-depth profile was chosen of the same type as in Figure 1 and with numerical values in agreement with the determinations by *Gutenberg* [1953] for *P* waves. The layering in the crust, that is, the uppermost 30–35 km in continental regions, was ignored. It may be necessary to take it into account in a second approximation. In the present case the velocity-depth profile was extended from 50 km depth to the surface with the same slope as below 100 km.

A profile with the following velocity values and with linearly varying velocity in each layer was assumed:

r_0 = 6370 km	v_0 = 7.8 km/sec
r_1 = 6320	v_1 = 8.0
r_2 = 6270	v_2 = 7.8

If h is used as variable and the velocity in layer A is expressed as $v = v_0 + \alpha h$, α being a constant, it is found that this leads to extremely complicated integrals for the travel times. It was found much easier to use r as a variable and to express v as an

exponential function of r. This gives, with the exponent $b > 0$

$$\left.\begin{aligned} &\text{for layer } A: && v = v_0(r/r_0)^{-b} \\ &\qquad B: && v = v_1(r/r_1)^{b} \\ &\qquad C: && v = v_2(r/r_2)^{-b} \end{aligned}\right\} \qquad (1)$$

Using the numerical values above, we find $b = 3.2$. I have chosen for simplicity $b = 3$. This choice gives the velocities listed in Table 1 and graphically shown in Figure 2. Equations (1) have the advantage of giving almost exactly linear variations of velocity with depth within the intervals we are concerned with, and also give relatively simple expressions for travel times, distances, etc.

Shadow zones—The shadow zone due to the existence of a low-velocity layer is obvious from Figure 1. In this section we shall compute the extent of the shadow zone, that is, its inner and outer radius for various focal depths. We therefore need expressions of the distances s corresponding to our profile, and we will then apply the boundary conditions of the shadow zone to these expressions.

An infinitesimal distance along a path at any depth has a horizontal projection equal to $-\tan i\, dr$ (on a down-going part of the path, that is, $dr < 0$). The corresponding distance ds on the surface is given by the following expression, taking the Earth's curvature into account

$$ds = -(r_0/r)\tan i\, dr \qquad (2)$$

There is symmetry with regard to the radius through the lowest point for every path. For a surface focus it is therefore sufficient to integrate ds over half the path and to double the result. The same naturally applies to any single layer.

The refraction law gives

$$\frac{r}{v}\sin i = \text{constant} \qquad (3)$$

along any given ray. For layers A and C we have from (1) that

$$v = \text{constant} \times r^{-b} \qquad (4)$$

Introducing (4) into (3) we get

$$r^{1+b}\sin i = \text{constant} \qquad (5)$$

Differentiation of (5) gives

$$\tan i\,\frac{dr}{r} = -\frac{di}{1+b} \qquad (6)$$

Combining (6) with (2) we get

$$ds = \frac{r_0\, di}{1+b} \qquad (7)$$

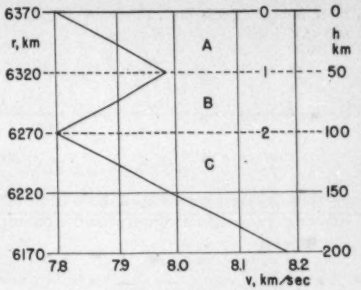

FIG. 2 – The assumed velocity profile for P waves

For layer B the corresponding formula is

$$ds = \frac{r_0\, di}{1-b} \qquad (8)$$

The formulas (7) and (8) are immediately integrable, r_0 and b being constants. Expressing i in radians, (7) and (8) give s in km. If we express i in degrees, the right-hand sides of (7) and (8) must then be multiplied by $\pi/180$. For instance, for a path in layer A passing from surface (0) to level 1 the corresponding surface distance is

$$s_A = \frac{\pi}{180}\int_{i_0}^{i_1}\frac{r_0\, di}{1+b} = \frac{\pi r_0}{180(1+b)}(i_1 - i_0) \qquad (9)$$

Similarly for layer B we get

$$s_B = \frac{\pi}{180}\int_{i_1}^{i_2}\frac{r_0\, di}{1-b} = \frac{\pi r_0}{180(1-b)}(i_2 - i_1) \qquad (10)$$

TABLE 1 – *Velocities of longitudinal waves according to the assumed profile*

Layer A		Layer C	
r	v	r	v
km	mkm/sec	km	km/sec
6370	7.800	6260	7.836
6360	7.837	6250	7.874
6350	7.874	6240	7.912
6340	7.912	6230	7.950
6330	7.949	6220	7.988
6320	7.986	6210	8.027
		6200	8.066
Layer B		6190	8.105
		6180	8.144
6310	7.948	6170	8.184
6300	7.911		
6290	7.873		
6280	7.836		
6270	7.798		

If we instead express both i and s in degrees, (7) and (8) simplify to the following

$$ds = \frac{di}{1+b} \tag{7'}$$

for layers A and C and

$$ds = \frac{di}{1-b} \tag{8'}$$

for layer B. These formulas will be used in the following. The formulas corresponding to (9) and (10) then read

$$s_A = \frac{i_1 - i_0}{1+b} \tag{9'}$$

and

$$s_B = \frac{i_2 - i_1}{1+b} \tag{10'}$$

The numerical values of the angles of incidence are all computed from (3) for any given value of one of them, that is

$$\frac{r_0 \sin i_0}{v_0} = \frac{r_1 \sin i_1}{v_1} = \frac{r_2 \sin i_2}{v_2} = \frac{r \sin i}{v} \tag{11}$$

The boundary conditions for the shadow zone are for the inner limit

$$i_1 = 90° \tag{12}$$

for the outer limit

$$\frac{ds}{di_h} = 0 \tag{13}$$

corresponding to a minimum of s (see Fig. 1).

All distances short of the shadow zones are computed from the following general expressions.

$$\left.\begin{aligned} &h = 0\text{–}50\text{:}\ s = \frac{1}{1+b}\,[-i_h + 2\,i_1 - i_0] \\ &h = 60\text{–}100\text{:} \\ &\quad s = \frac{1}{1+b}\left[\frac{1+b}{1-b}\,i_h - \frac{2b}{1-b}\,i_1 - i_0\right] \\ &h = 110\text{–}120\text{:} \\ &\quad s = \frac{1}{1+b}\left[i_h + \frac{2b}{1-b}\,(i_2 - i_1) - i_0\right] \end{aligned}\right\} \tag{14}$$

Combination with the condition (12) and equations (11) give the value of the inner radius of the shadow zone in each case, remembering that $b = 3$ and $i_h = i_0$ for $h = 0$, $i_h = i_1$ for $h = 50$, and $i_h = i_2$ for $h = 100$.

TABLE 2 – *Limits and width of the shadow zone on the Earth's surface*

h	Inner limit of shadow zone		Outer limit of shadow zone		Width of shadow zone
	i_h	s	i_h	s	
km	°	°	°	°	°
0	75.73	7.14	70.81	14.83	7.69
10	77.20	6.77	72.06	14.56	7.79
20	78.93	6.34	73.38	14.24	7.90
30	80.93	5.84	74.86	13.96	8.12
40	83.60	5.17	76.64	13.59	8.42
50	90.00	3.57	78.87	13.15	9.58
60	85.40	5.87	78.66	12.69	6.82
70	83.60	6.77	78.36	12.31	5.54
80	82.15	7.50	77.92	11.84	4.34
90	80.93	8.11	77.45	11.40	3.29
100	79.83	8.66	76.87	11.03	2.37
110	82.15	9.24	78.93	10.55	1.31
120	85.55	10.09	81.63	10.06	(−0.03)

For all distances beyond the shadow zone the following general formulas are valid.

$$\left.\begin{aligned} &h = 0\text{–}50\text{:}\ s = \frac{1}{1+b} \\ &\quad \cdot \left[180 - i_h + \frac{4b}{1-b}\,(i_2 - i_1) - i_0\right] \\ &h = 60\text{–}100\text{:}\ s = \frac{1}{1+b} \\ &\quad \cdot \left[180 - \frac{1+b}{1-b}\,i_h + \frac{2b}{1-b}\,(2i_2 - i_1) - i_0\right] \\ &h = 110\text{–}150\text{:}\ s = \frac{1}{1+b} \\ &\quad \cdot \left[180 - i_h + \frac{2b}{1-b}\,(i_2 - i_1) - i_0\right] \end{aligned}\right\} \tag{15}$$

Differentiation of these formulas according to the condition (13) leads to equations, which in each case may be solved, using also (11) both unchanged and differentiated with respect to the angles of incidence. It has to be remembered again that $b = 3$ and $i_h = i_0$ for $h = 0$, $i_h = i_1$ for $h = 50$, and $i_h = i_2$ for $h = 100$.

The results of the computations are presented in Table 2, giving also the angles of incidence at the source of the rays which limit the shadow zone.

The following results are obtained.

(1) The inner radius has its minimum for $h = 50$ km, that is, for a focus in the velocity maximum, and increases for both shallower and deeper foci.

(2) The outer radius decreases continuously for foci at $h = 0$ downward.

(3) The maximum width of the shadow zone is obtained for $h = 50$ km, that is, again for a focus in the level of velocity maximum.

(4) The shadow zone has disappeared for a focus at $h = 120$ km, that is, in our case 20 km below the level of minimum velocity.

Travel times—The travel time for an infinitesimal part of the path at any depth is given by

$$dt = \frac{|\,dr\,|}{v \cos i} \tag{16}$$

This equation may easily be integrated in the case of our profile, which will be demonstrated by deriving the formula for a surface focus, considering only layer A. For a ray corresponding to the inner limit of the shadow zone, that is, tangential at level 1, the total travel time is

$$t_A = -2\int_{r_0}^{r_1} \frac{dr}{v \cos i} \tag{17}$$

Both v and i are functions of r. We introduce v from (1) for layer A and put $\cos i = (1 - \sin^2 i)^{\frac{1}{2}}$ and

$$\sin i = \frac{r_0 \sin i_0}{v_0}\,\frac{v}{r} = \frac{r_0^{1+b} \sin i_0}{r^{1+b}}$$

by equations (1) and (11). Equation (17) then reads

$$t_A = \frac{2r_0^{-b}}{v_0}\int_{r_1}^{r_0} \frac{r^{1+2b}\,dr}{(r^{2+2b} - r_0^{2+2b}\sin^2 i_0)^{\frac{1}{2}}} = \frac{1}{v_0 r_0^{b}(1+b)}\int_{r_1}^{r_0} \frac{dr^{2+2b}}{(r^{2+2b} - r_0^{2+2b}\sin^2 i_0)^{\frac{1}{2}}}$$

Using r^{2+2b} as variable instead of r, this expression is readily integrated, giving

$$t_A = \frac{2r_0}{v_0(1+b)}\left\{\cos i_0 - \left[\left(\frac{r_1}{r_0}\right)^{2+2b} - \sin^2 i_0\right]^{\frac{1}{2}}\right\}$$

Combining (1) and (11), remembering that $i_1 = 90°$, we find that the last term is zero, and the result is

$$t_A = \frac{2r_0}{v_0(1+b)} \cos i_0 \tag{18}$$

Eq. (18) gives t_A as a function of i_0. The derivations of t for all other cases are completely analogous to the one given here.

The following formulas for t are obtained; the numerical formulas give t in sec for P waves.

(1) At distances short of the shadow zone, when $h = 0$

$$t = t_A = \frac{2r_0}{v_0(1+b)} \cos i_0 = 408.3333 \cdot \cos i_0 \tag{19a}$$

when $h = 50$

$$t = t_A = \frac{r_1}{v_1(1+b)} \cdot \left\{\left[\left(\frac{r_0}{r_1}\right)^{2+2b} - \sin^2 i_1\right]^{\frac{1}{2}} - \cos i_1\right\} = 197.8462\,[(1.0650 - \sin^2 i_1)^{\frac{1}{2}} - \cos i_1] \tag{19b}$$

when $h = 100$

$$t = t_A + t_B = \frac{r_2}{v_2(1+b)}\left\{\left[\left(\frac{r_0}{r_2}\right)^2\left(\frac{v_2}{v_0}\right)^2 - \sin^2 i_2\right]^{\frac{1}{2}} - \left[\left(\frac{r_2}{r_1}\right)^{2b-2} - \sin^2 i_2\right]^{\frac{1}{2}}\right\} + \frac{r_2}{v_2(b-1)} \cdot \left\{\cos i_2 - \left[\left(\frac{r_2}{r_1}\right)^{2b-2} - \sin^2 i_2\right]^{\frac{1}{2}}\right\} = 201.0131\,[(1.0315 - \sin^2 i_2)^{\frac{1}{2}} - 3(0.9688 - \sin^2 i_2)^{\frac{1}{2}} + 2\cos i_2] \tag{19c}$$

(2) Beyond the shadow zone, when $h = 0$

$$t = t_A + t_B + t_C = \frac{2r_0}{v_0(1+b)}\left\{\cos i_0 - \left[\left(\frac{r_1}{r_0}\right)^{2+2b} - \sin^2 i_0\right]^{\frac{1}{2}}\right\} + \frac{2r_0}{v_0(b-1)}\left\{\left[\left(\frac{r_2}{r_0}\right)^2\left(\frac{v_0}{v_2}\right)^2 - \sin^2 i_0\right]^{\frac{1}{2}} - \left[\left(\frac{r_1}{r_0}\right)^{2+2b} - \sin^2 i_0\right]^{\frac{1}{2}}\right\} + \frac{2r_0}{v_0(1+b)}\left[\left(\frac{r_2}{r_0}\right)^2\left(\frac{v_0}{v_2}\right)^2 - \sin^2 i_0\right]^{\frac{1}{2}} = 1225.0000\left[\frac{\cos i_0}{3} + (0.9693 - \sin^2 i_0)^{\frac{1}{2}} - (0.9390 - \sin^2 i_0)^{\frac{1}{2}}\right] \tag{20a}$$

when $h = 50$

$$t = t_A + t_B + t_C = \frac{r_1}{v_1(1+b)} \cdot \left\{\left[\left(\frac{r_0}{r_1}\right)^{2+2b} - \sin^2 i_1\right]^{\frac{1}{2}} - \cos i_1\right\} + \frac{2r_1}{v_1(b-1)} \cdot \left\{\left[\left(\frac{r_2}{r_1}\right)^{2-2b} - \sin^2 i_1\right]^{\frac{1}{2}} - \cos i_1\right\} + \frac{2r_1}{v_1(1+b)}\left[\left(\frac{r_2}{r_1}\right)^{2-2b} - \sin^2 i_1\right]^{\frac{1}{2}} = 197.8462[(1.0650 - \sin^2 i_1)^{\frac{1}{2}} + 6(1.0324 - \sin^2 i_1)^{\frac{1}{2}} - 5\cos i_1] \tag{20b}$$

when $h = 100$

$$t = t_A + t_B + t_C = \frac{r_2}{v_2(1+b)} \cdot \left\{\left[\left(\frac{r_0}{r_2}\right)^2\left(\frac{v_2}{v_0}\right)^2 - \sin^2 i_2\right]^{\frac{1}{2}} - \left[\left(\frac{r_2}{r_1}\right)^{2b-2} - \sin^2 i_2\right]^{\frac{1}{2}}\right\} + \frac{r_3}{v_2(b-1)} \cdot \left\{\cos i_2 - \left[\left(\frac{r_2}{r_1}\right)^{2b-2} - \sin^2 i_2\right]^{\frac{1}{2}}\right\} + \frac{2r_2}{v_2(1+b)} \cos i_2$$

$$= 201.0131\,[(1.0315 - \sin^2 i_2)^{\frac{1}{2}} - 3(0.9688 - \sin^2 i_2)^{\frac{1}{2}} + 4\cos i_2] \qquad (20c)$$

Each of the equations (19) and (20) gives the travel time as a function of the angle of incidence at the source. Eq. (14) and (15) together with (11) express the distances similarly. The equation system

$$\left.\begin{aligned} t &= t(i_h) \\ s &= s(i_h) \end{aligned}\right\} \qquad (21)$$

defines the travel time curve in each case. Elimination of the parameter i_h between the two equations (21) is not easily done. Computations have therefore been made both of t and of s, starting from given values of i_h.

Travel times have been determined for the focal depths 0, 50, and 100 km. The results are given in Figures 3 to 5 and in Table 3. The values in Table 3 (for equal integers of s) were determined by interpolation from the directly computed values, and also subject to smoothing to remove some slight mathematical scatter.

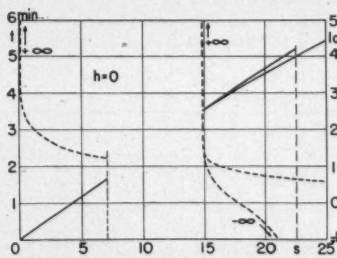

FIG. 3 – Travel times (t, solid curves) and logarithm of energies in an arbitrary unit (log ϵ, dashed curves) for P waves for $h = 0$ km

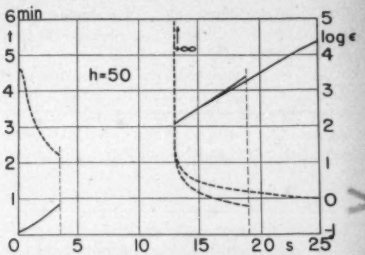

FIG. 4 – Travel times (t, solid curves) and logarithm of energies in an arbitrary unit (log ϵ, dashed curves) for P waves for $h = 50$ km

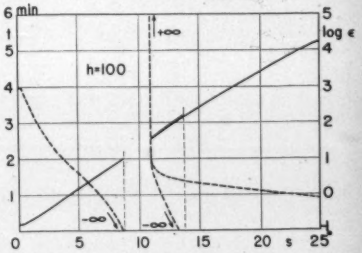

FIG. 5 – Travel times (t, solid curves) and logarithm of energies in an arbitrary unit (log ϵ, dashed curves) for P waves for $h = 100$ km

In conclusion the following points are emphasized.

(1) Beyond the shadow zone the travel time curves have two branches due to the assumption of a low-velocity layer. The second, later branch exists up to $s = 22°.45$ for $h = 0$, to $s = 18°.84$ for $h = 50$, and to $s = 13°.75$ for $h = 100$.

(2) The travel-time curves at distances short of the shadow zone and beyond the shadow zone can in each case be connected by a continuous curve through the shadow zone, as the two parts short of and beyond the shadow zone point directly towards each other. This remark constitutes a correction to the more qualitative curves shown in Figure 1. The curve interpolated through the shadow zone is expected to give travel times for waves, due to diffraction, considered below.

(3) Comparison with observed travel times of P waves, which is not attempted here, may require

TABLE 3 – *Travel times of longitudinal waves for focal depths 0, 50, and 100 km corresponding to our velocity profile*

h = 0 km			h = 50 km			h = 100 km		
s	t		s	t		s	t	
	min	sec		min	sec		min	sec
0°	0	0.0	0°	0	6.3	0°	0	12.6
1	0	14.3	1	0	15.5	1	0	18.7
2	0	28.5	2	0	28.8	2	0	30.6
3	0	42.7	3	0	42.5	3	0	43.6
4	0	56.8	3.57	0	50.5	4	0	57.2
5	1	10.9				5	1	10.9
6	1	24.9	13.15	3	5.5	6	1	24.6
7	1	38.8	14	3 16.7	3 17.3	7	1	38.4
7.14	1	40.7	15	3 29.6	3 31.2	8	1	52.3
			16	3 42.4	3 45.0	8.66	2	1.5
14.83	3	29.4	17	3 54.9	3 58.7			
15	3 31.4	3 31.8	18	4 7.0	4 12.5	11.03	2	34.7
16	3 44.5	3 45.7	18.84		4 24.1	12	2 47.8	2 48.6
17	3 57.4	3 59.8	19	4 18.8		13	3 1.0	3 2.3
18	4 9.9	4 14.1	20	4 30.2		13.75		3 12.3
19	4 22.0	4 28.1	21	4 41.3		14	3 14.0	
20	4 33.7	4 41.8	22	4 52.0		15	3 26.7	
21	4 45.0	4 55.0	23	5 2.4		16	3 39.2	
22	4 55.9	5 7.5	24	5 12.5		17	3 51.4	
22.45		5 13.2	25	5 22.4		18	4 3.2	
23	5 6.5					19	4 14.8	
24	5 16.8					20	4 26.1	
25	5 26.9					21	4 37.1	
						22	4 47.7	
						23	4 58.0	
						24	5 7.8	
						25	5 17.2	

slight variation of the assumed velocity profile including consideration of the crustal layers.

Energy—The following assumptions are made in the computation of the energy of the direct P waves. (1) The focus is a point-source of energy. (2) There is equal radiation of energy in all directions from the source. This may deviate considerably from the real energy distribution. However, the method followed below can be applied to any earthquake model with known energy radiation. (3) Energy losses due to scattering and other phenomena will be neglected. Such effects will be discussed later. (4) Only the direct P waves are considered. Energy arriving at the surface of the Earth by way of reflections at the surface, for example, as pP or PP waves, is not considered here.

With these assumptions it is true that the energy emitted within a certain solid angle $d\omega$ at the source, corresponding to an interval di of the angle of incidence at the source, arrives at the surface of the Earth within a circular, ring-shaped area of the corresponding width ds. Looking at Figure 1 we have to consider that the real, three-dimensional picture is obtained by rotating each figure around the vertical through the focus H. With the notation indicated earlier, the following relation is obtained

$$E_0 \frac{d\omega}{4\pi} = E_0 \frac{2\pi \sin i \, di}{4\pi} = e \cdot 2\pi r_0^2 \sin s \, ds$$

This gives

$$\frac{4\pi r_0^2 e}{E_0} = \frac{\sin i}{\sin s} \left| \frac{di}{ds} \right| \tag{22}$$

The quantity ϵ is defined as follows

$$\epsilon = \frac{4\pi r_0^2 e}{E_0(1+b)} = \frac{1}{1+b} \frac{\sin i}{\sin s} \left| \frac{di}{ds} \right| \tag{23a}$$

or

$$\log \epsilon = \log \frac{4\pi r_0^2}{E_0(1+b)} + \log e \tag{23b}$$

ϵ is directly proportional to the energy e per unit surface area, all other quantities in (23) being constants. The factor $(1 + b)$ is included in the definition of ϵ so as to cancel the corresponding factor appearing in di/ds. Account has been taken of the fact that in the case of $h = 0$ the energy is radiated in a half-space, that is, within a solid angle $= 2\pi$ instead of 4π. The same total energy E_0 of the P

TABLE 4 – *Variation of log ϵ with distance along the Earth's surface for focal depths of 0, 50, and 100 km*

h = 0 km			h = 50 km			h = 100 km		
s	log ϵ		s	log ϵ		s	log ϵ	
0°	+∞		0°	3.62		0°	3.00	
1	2.06		1	2.50		1	2.48	
2	1.76		2	1.76		2	1.83	
3	1.58		3	1.36		3	1.34	
4	1.45		3.57	1.21		4	0.96	
5	1.35					5	0.61	
6	1.27		13.15	+∞		6	0.28	
7	1.20		14	0.63	0.43	7	−0.10	
7.14	1.19		15	0.48	0.19	8	−0.63	
			16	0.39	0.03	8.66	−∞	
14.83	+∞		17	0.32	−0.06			
15	1.36	1.14	18	0.26	−0.14	11.03	+∞	
16	1.03	0.53	18.84		−0.21	12	0.57	−0.09
17	0.93	0.21	19	0.21		13	0.46	−0.74
18	0.85	−0.06	20	0.16		13.75		−∞
19	0.80	−0.27	21	0.12		14	0.38	
20	0.75	−0.57	22	0.08		15	0.32	
21	0.71	−0.92	23	0.04		16	0.27	
22	0.67		24	0.00		17	0.22	
22.45		−∞	25	−0.03		18	0.18	
23	0.63					19	0.14	
24	0.59					20	0.10	
25	0.55					21	0.07	
						22	0.03	
						23	−0.01	
						24	−0.04	
						25	−0.08	

waves is assumed in all cases, and the computed values of ϵ do not only show the energy variation with distance s for a given depth, but can also be used for comparison of different focal depths at a given distance.

The value of ϵ has been computed for the focal depths h = 0, 50, 100 km, using (23a) in combination with (14) and (15) for s and the refraction law (11), differentiated with respect to the angles of incidence. In (23a) $i = i_0$ for $h = 0$, $i = i_1$ for $h = 50$, and $i = i_2$ for $h = 100$, because in the derivation of the energy expression, i always means the angle of incidence at the source. The results, giving log ϵ, are shown in Figures 3 to 5 and in Table 4.

A few points in the results may need explanation. An infinite value of ϵ has been obtained for $h = 0$, $s = 0$, which is a consequence of the assumption of a point-source. Likewise, infinite ϵ is obtained in every case at the caustic immediately beyond the shadow zone, this being a consequence of the boundary condition (13) for the shadow zone. In fact, a total infinite energy cannot be reached at any place, as the given energy E_0 is finite. ϵ is proportional to the energy per unit area of the Earth's surface, and in the cases mentioned the area receiving the energy is zero.

At the epicenter, $s = 0$ and $i = 0$ and $\sin i/\sin s$ appearing in (23a), becomes indeterminate, whereas other factors have finite and definite values. The limiting value is as follows

$$\lim_{s=0} \frac{\sin i}{\sin s} = \left|\frac{di}{ds}\right|_{s=0}$$

and the corresponding value of ϵ is

$$(\epsilon)_{s=0} = \frac{1}{1+b}\left|\frac{di}{ds}\right|^2_{s=0} \tag{24}$$

The energy curves for $h = 50$ and $h = 100$ have horizontal tangents for $s = 0$. It may be shown from our formulas that for $h > 0$

$$\left(\frac{d\epsilon}{ds}\right)_{s=0} = 0 \tag{25}$$

It has not been attempted to give the amplitudes, which would be recorded at the surface. The amplitudes would not simply be proportional to the square roots of ϵ, but the effects of the reflection at the surface must then also be taken into account.

Computing the fraction of the total energy E_0 of the P waves which passes into the channel and remains there (see Fig. 1), we find by the ray theory a zero value for $h = 0$ km and $h = 50$ km and a finite value only for $h = 100$ km out of the three focal depths considered. For $h = 100$ km the fraction of E_0 passing into channel waves amounts to 0.18 (= cos 79°.83; see Table 2). Channel-wave studies indicate, however, that a much larger fraction of the total energy is contained in channel waves than is obtained from the simple ray theory.

The following conclusions are obtained from the energy computations.

(1) The energy decreases rapidly with distance inside the inner limit of the shadow zone, reaching zero value for $h = 100$ km at the inner limit. This makes determinations of the location of the inner limit difficult from observations. For other effects of importance in this connection see *Other effects*.

(2) The outer limit of the shadow zone shows in all cases a high energy concentration, which would facilitate its discovery from observations.

(3) Comparing the two branches beyond the shadow zone there is in every case much less energy on the second, later branch than on the

first. This may make it difficult to discover the second branch in seismic records.

(4) The energy curves in Figures 3 to 5 demonstrate that, in the presence of a low-velocity layer, the variation of energy with distance is far more complicated than any simple relation to distance can express. This is of importance in deducing magnitude formulae for distances below about 25°. In this connection differences in local structure are also of considerable importance.

Other effects—The theory developed so far has been concerned only with the simplest case, dealing only with *P* waves and using only the classical ray theory. In this section various extensions and improvements will be mentioned, some of which I hope will be investigated in more detail in the future.

The theory developed above could immediately be applied to a similar study of *S* waves. A somewhat different velocity profile has to be assumed [see *Gutenberg*, 1953]. The results would double the number of possibilities of comparison with actual records of earthquakes, both with regard to the extent of the shadow zone, travel times, and energies.

The most serious discrepancy between the theory developed here and observations is the fact that waves are observed also within the shadow zone, although weaker than outside. Part of this can be explained by ray theory, taking account of minor effects which were neglected above (a and b below), part of it is explained by other factors beyond the reach of the ray theory (c and d, and partly e below). Common to all these effects (a) to (e) is that the travel-time curves computed above are left unchanged, whereas the energy curves are slightly modified. This is obvious from the fact, that the total energy E_0 is constant, and the energy passing into the shadow zone must therefore be taken from areas outside, which means a modification of the energy curves, already computed.

The following effects, neglected above, must be considered in a second approximation.

(a) Reflections from the free surface. These can explain part of the motions within the shadow zone, but the waves will in general not arrive on the travel time curve interpolated through the shadow zone (see *Travel times*, above). They will instead account for some of the later motion observed.

(b) Reflections and refractions at internal discontinuities. The crustal layering (especially in continental areas) may give rise to reflected and refracted waves, throwing part of the energy into a shadow zone. Our assumed profile with a velocity gradually varying with depth implies that the medium is continuously changing its properties with depth. In such a case a minute fraction of the incident energy is reflected at every level, which may also contribute to energy observed within the shadow zone. Some of these waves are expected to conform to the interpolated travel time curve.

(c) Scattering. This is due to inhomogeneities in the Earth, especially in the crust, implying irregularities of the wave velocities. The scattering is known to be of very great significance, especially for the shorter waves and in the crust. This effect will certainly account for an essential part of the energy arriving inside the shadow zone, but again it is not expected to conform to the interpolated travel-time curve. In fact, scattering may explain arrivals earlier than the interpolated travel-time curve with the consequence that phases become unclear within the shadow zone. In order to be computed quantitatively, special assumptions regarding the inhomogeneity are required.

(d) Diffraction. This effect may possibly account for the main part of the energy arriving inside the shadow zone. The diffraction phenomena are analogous to those due to the outer core boundary. In the case of the core, however, amplitudes especially for shorter periods in excess of those computed by diffraction theory are observed within the corresponding shadow zone. This is explained by reflections and refractions of waves at the boundary of the inner core. Such a complication does not occur in our case, but otherwise the phenomena are closely related. The diffracted waves are also expected to account at least for most of the initial motion within the shadow zone. In fact, diffraction phenomena are certainly just as important in continued studies of the present problem as they are in the study of the rain-bow.

(e) Channel waves in the crust may also play a role.

Seismic model experiments may prove very valuable in investigating the complicated wave phenomena associated with a low-velocity layer.

Acknowledgments—This investigation was started at the Seismological Laboratory of Uppsala, where also most of the computations were made. The work was finished at the Seismological Laboratory of Pasadena during my visit there as a Research Associate in Geophysics of the California Institute of Technology. My best thanks are due to B. Gutenberg and C. F. Richter

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The Reproducibility of A^{40}/K^{40} Age Determinations

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Abstract—Techniques used in A^{40}/K^{40} age determinations are discussed. The reproducibility of the method as studied by replicate determinations on the same sample and on different samples from a rock unit is within five per cent of the age of the rock. A^{40}/K^{40} age determinations are given for a group of samples, and the results are compared with ages obtained in other laboratories using the same samples.

Introduction

Improvements in A^{40}/K^{40} dating within recent years through the work of a number of laboratories in the United States and Canada have made this method a valuable geologic tool. In connection with a project to date a large number of rocks from Minnesota and the Lake Superior region, the procedures and analytical reliability of A^{40}/K^{40} determinations were investigated. Basically, the method involves the quantitative determination of K^{40} and one of its decay products, A^{40}.

Analytical Procedures

Argon extraction—The techniques used in the extraction of radiogenic argon are essentially the same as those of *Wetherill* and co-workers [1956], except for a different method of sample introduction and the general use of pyrophoric uranium as a chemical getter to clean up the argon. It was also found advantageous to use all-glass thermocouple pressure gauges to follow the clean-up procedures.

To facilitate preliminary outgassing of the sample and subsequent introduction into the NaOH flux, the sample is weighed into a small glass ampule. The ampule is open to permit outgassing of the sample, and is suspended above the fusion crucible from a short iron rod contained in a horizontal glass sheath. Following the outgassing period the sample can be dropped on the solidified flux by withdrawing the iron rod with a magnet. In this manner the sample is outgassed along with the train, is completely introduced into the flux without loss, and is contained within the bulb so that upward 'blowing' of the sample at the beginning of the fusion is minimized. The thin glass ampule can be made to weigh less than one-tenth of the sample weight and is completely dissolved in the NaOH flux. The high sensitivity of the mass spectrometer employed permits a small sample (1–4 gm) to be used, and complete fusion of the sample is easily obtained.

In addition to a $Mg(ClO_4)_2$ trap, a CuO trap, and a tungsten filament, a pyrophoric uranium trap is used to rapidly and efficiently clean up the argon. This getter is easily prepared in the trap itself by converting the uranium to the hydride at 250°C in a hydrogen atmosphere, slowly heating the hydride to 500°C and pumping off the evolved hydrogen until the remaining powder is thoroughly outgassed. Upon conversion to the hydride, uranium metal breaks down into a pyrophoric powder, and with careful decomposition retains this form upon reconversion to the metal. The resulting uranium powder actively getters all the gases not previously removed in the purification procedure except the rare gases. Efficient temperatures for its gettering action are less than 500°C so that pyrex glass may be used in the construction of the trap.

Three blank runs were made on the extraction train in exactly the same manner as a regular run, except that no sample was used. The argon blank was found to be 1.6 to 1.7 $\times 10^{-7}$ cc STP of A^{40} and less than 4×10^{-10} cc STP of A^{36} and of A^{38} per run. For samples containing much radiogenic argon (10^{-3}–10^{-4} cc STP of A^{40}/gm) the described outgassing of the sample is adequate. For samples containing smaller amounts of radiogenic argon (10^{-5}–10^{-6} cc STP/gm) the air argon no longer is negligible, and the sample must be thoroughly outgassed. This can be accomplished by heating the sample to 200° C during the outgassing. A convenient arrangement consists of a small heating unit wrapped around the glass tubing where the sample is suspended.

A^{38} spikes—The A^{36}/A^{38} and A^{40}/A^{38} ratios in the spike argon were carefully measured for each of five spike sets and found to be the same within one per cent for all but one set in which minor air leakage was indicated.

The spikes were calibrated after the method of *Wasserburg* and *Hayden* [1955]. A direct comparison between the spike sets was made with the mass spectrometer. A spike was quantitatively pumped into the recirculation system of the mass spectrom-

eter, and the height of the A^{38} peak, as well as of the other isotopes, noted. The procedure was repeated for a spike from each set, care being taken to insure that the absolute response of the mass spectrometer did not change during the tests. The relative A^{38} peak heights were compared with the predictions from the mixing procedures, and the results indicated that the five spike sets checked one another within two per cent.

Argon isotope measurements—The first argon isotope determinations in the present investigation were run on a double-focussing mass spectrometer. This high-resolution instrument employs a highly effective differential pumping system between the source region and the analyzer. The entire sample to be analyzed is introduced into the source region and circulated through a trap containing pyrophoric uranium. The rate of leakage from the source region is so slow that samples could be run 20–30 minutes without a serious decay of the peaks.

All of the recent work has been done with a high-sensitivity, six-inch, Nier-type instrument employing a closed recirculating system with a uranium getter trap. The sensitivity is such that 10^{-5} cc STP of gas produces an ion current of approximately 2×10^{-10} amperes. The heights of the argon peaks will remain constant for several hours. The inleakage of argon and residual impurities in the argon region are essentially negligible. Quantitative analyses of 10^{-6} cc STP of argon are readily made.

Potassium determination—All the potassium determinations were made in the Rock Analysis Laboratory by the J. Lawrence Smith fusion method [*Goldich* and *Oslund*, 1956]. Double fusions and extractions are made on all samples exceeding five per cent K_2O. Laboratory blanks are run periodically, and during the last year the K_2O blank ranged from 0.01_2 to 0.03_2 per cent K_2O (to be subtracted from the determined K_2O). Rubidium and cesium are determined with a flame spectrophotometer and appropriate corrections made. A precision of one per cent in the range of one to 14 per cent K_2O is normal. The K^{40} content of the sample is calculated on the basis $K^{40}/K = 0.000119$.

TABLE 1 – *Reproducibility of A^{40}/K^{40} on the same sample*

Description	K	A^{40}/K^{40}
	pct	
O-S-A, Dickinson County, Mich. Microcline	9.78	0.0942
		0.0937
	9.79	0.0955
		0.0946
O-S-H, Spruce Pine District, N. C. Muscovite—Chestnut Flat	8.43	0.0211
		0.0223
O-S-D, Bikita, South Rhodesia Lepidolite	7.30	0.278
	7.37	0.274
O-S-F, Portland, Conn. Lepidolite	8.70	0.0153
	8.71	...
KA-14, Morton gneiss, Minn. Biotite	6.74	0.326
		0.322
KA-4, Kinmount pegmatite, Minn. Biotite	6.42	0.286
		0.300
KA-57, Milbank granite, S. Dak. Biotite	6.35	0.211
	6.30	0.206
KA-28, Granite Falls granite, Minn. Biotite	6.01	0.165
		0.161
KA-93, Mellen granite, Wis. Biotite	4.80	0.0796
		0.0760
KA-126, Canadian granite, B. C. Biotite	6.39	0.00580
		0.00615

TABLE 2 – *Reproducibility of A^{40}/K^{40} on similar samples*

Sample locality	K	A^{40}/K^{40}	Age × 10^{-9} [a]
	pct		year
Minnesota Valley, Minn.			
Morton gneiss			
No. 14 (biotite)	6.74	0.324	2.65
No. 51 (biotite)	6.18	0.314	2.61
Sacred Heart granite			
No. 9 (biotite)	5.42	0.289	2.50
No. 13 (biotite)	5.67	0.295	2.53
No. 23 (biotite)	3.97	0.296	2.53
Montevideo granite gneiss			
No. 25 (biotite)	4.92	0.177	1.87
No. 27 (biotite)	4.92	0.175	1.85
No. 54 (biotite)	5.49	0.170	1.82
Spruce Pine district, N. C.			
Hoot Owl (muscovite)	8.47	0.0225	0.365
McKinney (muscovite)	8.20	0.0222	0.362
Chestnut Flat (muscovite)	8.43	0.0211	0.345
	8.43	0.0223	0.363

[a] A^{40}/K^{40} ages calculated using $\lambda_e = 0.557 \times 10^{-10}$/yr, $\lambda_\beta = 4.72 \times 10^{-10}$/yr.

Analytical Results

Good precision is attainable in the determination of potassium, in preparation and calibration of the A^{38} spikes, and in isotopic analysis of argon. The overall precision of the method, however, is dependent on many additional factors and operations which cannot be evaluated singly, and recourse was made to replicate determinations to study the overall reproducibility.

Replicate determinations made on 24 different samples show an average difference of 3.4 pct and a maximum difference of nine per cent. Data for some of these samples, ranging from 100 to 2500 million years in age, are given in Table 1.

Determinations made on different samples of

TABLE 3 – *Comparison of results on interlaboratory check samples*

Description	K	A^{40}/K^{40}	Age $\times 10^{-9}$	Other methods, age $\times 10^{-9}$
	pct		year	year
Dickinson Co., Mich.	9.79[b]	0.0945[b]	(1.22)	...
Microcline	9.62[e]	0.0962[e]	(1.23)	...
	9.67[d]	0.0937[d]	(1.21)	...
	9.46[e]	0.0936[e]	(1.21)	...
Spruce Pine District, N. C.				
Hoot Owl Mica	8.47[b]	0.0225[b]	0.365	...
	8.60[e]	0.0213[e]	0.346	...
McKinney Mica	8.20[b]	0.0222[b]	0.362	...
	8.24[e]	0.0218[e]	0.356	...
Chestnut Flat Mica	8.43[b]	0.0217[b]	0.354	0.375[i] (U-Pb)
	8.93[e]	0.0213[f]	0.346	0.370[i] (Rb-Sr)
San Diego, Calif. (Pala)				
Lepidolite	8.42[b]	0.00574[b]	0.100	0.106[g] (Rb-Sr)
Bikita, S. Rhodesia	7.33[b]	0.276[b]	2.44	2.65[h] (U-Pb)
Lepidolite	7.2[e]	0.279[e]	2.45	2.68[i] (Rb-Sr)
Portland, Conn.	8.70[b]	0.0153[b]	0.254	0.267[j] (U-Pb)
Lepidolite	8.44[d]	0.0158[d]	0.267	
		0.0158[f]	0.267	
Cardiff Twp., Ontario	7.42[b]	0.0776[b]	1.04	1.02[i] (U-Pb)
Biotite		0.0729[f]	1.00	1.00[i] (Rb-Sr)

[a] A^{40}/K^{40} ages calculated using $\lambda_e = 0.557 \times 10^{-10}$/yr, $\lambda_\beta = 4.72 \times 10^{-10}$/yr.
[b] Minnesota (average values in case of replicate determinations).
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similar rocks in one locality, such as muscovite from pegmatites of the Spruce Pine District, North Carolina, gave the same reproducibility as the checks on the same sample. Some of these data are given in Table 2. Variations in K-content in these samples (Table 2) is not a measure of precision, but reflects difference in mineral separations.

In Table 3, A^{40}/K^{40} determinations on the same sample by different laboratories are given. As is well known, precision of an analytical procedure in a single laboratory can be expected to be better than that of a number of laboratories. This is borne out in Table 3. The indicated reproducibility of five per cent is encouraging, but special attention has been given to these samples, and the results are probably not typical of routine runs.

CONCLUDING REMARKS

The value of radioactive dating to geologic investigations needs no elaboration. The A^{40}/K^{40} method is particularly attractive, and studies now in progress by a number of laboratories will materially improve our knowledge and application of the method. Additional studies of the precision and improvement of techniques are needed. At present a reproducibility of better than five per cent is possible, but requires exacting work. A five per cent deviation in age for a Precambrian rock two billion years old amounts to 100 million years. This is a very long time, equivalent roughly to the whole of the Mesozoic or geologic time since the Cretaceous, and geologists need only think of the events that took place during the Tertiary to realize its significance. A^{40}/K^{40} dates are being brought into line with U/Pb and Rb/Sr dates as can be seen from Table 3.

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Some Recent Harwell Analytical Work on Geochronology

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Abstract—Ages have been found by the rubidium-strontium method for the pair of meteorites (Forest City, a chondrite, and Johnstown, an achondrite) and for four lepidolites. The rubidium determinations made by stable isotope dilution are supported by neutron activation analysis. A brief mention is also made of the determination of lead in small samples of monazites by direct polarographic analysis.

Rubidium-Strontium Age Determination

Introduction—Previous geochemical work in this laboratory has been mainly concerned with elemental abundance determinations, using the techniques of neutron activation and stable isotope dilution. Methods for both rubidium and strontium had been developed, giving in most cases excellent agreement by the two techniques, and it was natural to extend the work to Rb-Sr age determinations in connection with the raw materials program of the United Kingdom Atomic Energy Authority. As a first step in contributing to the latter and as newcomers to the geochronological field, we chose to repeat and if possible extend somewhat *Schumacher's* [1956abcd] work on stone meteorites, and to determine ages for two lepidolites from the international intercomparison suite distributed under the direction of L. H. Ahrens and two that were available from Tanganyika.

Experimental procedure for the isotope dilution work: Chemical treatment of samples—The meteorites were washed with a small quantity of cold demineralised water, dried, and then ground or drilled; the metallic phase was not separated. The lepidolites were analysed as received.

The chemical treatment used was similar to that described by *Aldrich* [1956]. For the meteorites, weighed quantities of the solutions of rubidium and strontium tracers were added to the samples which were then attacked with hydrofluoric and perchloric acids and finally dissolved in hydrochloric acid. The rubidium and strontium were separated by ion exchange chromatography on a column of zeocarb 225 by elution with 2.5N hydrochloric acid. The treatment of the lepidolites differed in that the rubidium tracer was added only to a small aliquot of the solution of the sample which was then used directly for the rubidium determination. The final solutions were treated to yield rubidium sulphate and strontium nitrate for the mass spectrometric analysis.

The tracers were calibrated by isotope dilution with solutions prepared from normal rubidium chloride or strontium carbonate.

Mass spectrometry—All the rubidium samples, and the strontium samples from the lepidolites, were analysed in a 6-inch radius of curvature-60° mass spectrometer equipped with a Type 954 electrometer valve and a d c amplifier, and a surface ionisation source containing a single tungsten filament.

The strontium analyses for the meteorites were made with a Metropolitan Vickers Type MS5 mass spectrometer. This is a 12-inch radius of curvature, 90° machine equipped with an electron multiplier and a triple filament ion source; the samples were mounted on one of the side filaments. A multiplier correction of (atomic weight ratio)$^{\frac{1}{2}}$ was applied to all ratios measured with this machine. In order to obtain an accurate comparison of the isotopic composition of the strontium extracted from the two meteorites, these samples were analysed alternately several times under the same mass spectrometric conditions. The high resolution of the machine enabled interference fron background peaks to be avoided.

A comparison of results found for strontium samples analysed on the two machines shows that relative to ^{88}Sr, ratios obtained with the multifilament source are higher by about one per cent per mass unit than those found with the single filament source in the smaller machine.

Results and discussion—Ages have been calculated by assuming a half-life 5.0×10^{10} years for the decay of ^{87}Rb, that is, the value recommended by *Aldrich, Davis, Tilton* and *Wetherill* [1956].

Meteorites—As meteorite samples we had available very limited quantities of Forest City, one which Schumacher had included, and also Johnstown which, by neutron activation, had been shown [*Cabell* and *Smales*, 1957] to be very much lower in rubidium content than any quoted by Schumacher. As it turned out, the strontium in

TABLE 1 – *The rubidium and strontium contents of Forest City (AMNH 1007)*

Mass of sample	μgm Rb/gm	μgm Sr/gm	Ratio Rb/Sr	Mean atomic ratio	μgm Rb/gm by neutron activation
gm					
0.7784	2.97	10.5	0.283		
1.1401	2.77	9.6	0.287	0.291	3.01
1.0124	2.85	9.7	0.293		3.06
0.7472	3.00	11.0	0.272		
Mean value	2.90	10.2	0.284	...	3.04

TABLE 2 – *The rubidium and strontium contents of Johnstown (AMNH 2497)*

Mass of sample	Rb/gm	Sr/gm	Mean atomic ratio Rb/Sr	μgm Rb/gm by neutron activation
gm	μgm	μgm		
0.5398	0.108	2.05	...	0.04
0.3889	0.104	2.08	0.0518	0.05
1.3265	0.103	...	...	...
Mean value	0.105	2.07	...	0.04

TABLE 3 – *Calculated percentages of ^{87}Sr*

Meteorite	^{87}Sr
	pct
Forest City	7.389
Johnstown	6.977

Johnstown was also very low and there was no particular advantage in using that meteorite except to make us refine the procedure to work with very small quantities of strontium. Tables 1 and 2 record the rubidium and strontium analyses made by isotope dilution, and for comparison, the results for rubidium found previously by neutron activation [*Cabell* and *Smales*, 1957].

The value found for the $^{87}Sr/^{86}Sr$ isotope ratio of the strontium in each of the two meteorites has been corrected for contamination during the chemical treatment assuming this to be caused by common strontium. This correction changes that ratio by one part in 10,000 in the case of Forest City and by one part in 1300 for Johnstown. Table 3 records the percentages of ^{87}Sr calculated from the corrected ratios.

By using the relations derived by Schumacher and making similar assumptions, an age for stone meteorites may be calculated from the results in Tables 1–3, thus

$$\text{Age} = \frac{T\frac{1}{2}}{0.30103} \log_{10}\left[1 + \frac{x_1 - x_0}{0.2785\ R_1\ (1 - x_0)}\right]$$

$$x_0 = \frac{(x_2 R_1 - x_1 R_2)}{(R_1 - R_2)}$$

where

x_0 is the abundance of ^{87}Sr in primordial strontium

x_1 is the abundance of ^{87}Sr for Forest City

x_2 is the abundance of ^{87}Sr for Johnstown

R_1 is the Rb/Sr atomic ratio for Forest City

R_2 is the Rb/Sr atomic ratio for Johnstown

If the isotope ratios obtained directly from the multifilament source are assumed to be correct, the results found are

age = $4.64 \pm 0.44 \times 10^9$ years $\quad x_0 = 6.89$ pct

If the isotope ratios that have been corrected to the conditions for a single filament source in a mass spectrometer with a simple ion detector are assumed to be correct, the values are

age = $4.6 \pm 0.44 \times 10^9$ years $\quad x_0 = 6.82$ pct

The value found for the meteoritic age is thus $4.6 \pm 0.5 \times 10^9$ years, where the uncertainty is approximately three times the total standard error. This result agrees well with that found by

TABLE 4 – *Analyses and ages of lepidolites*

Sample	Rb by neutron activation	Rb by isotope dilution	Sr	Age
	pct	pct	ppm	m y
N45	3.40	3.29	346	2630
Bikita Quarry, So. Rhodesia	3.42	3.32	342	2570
Mean value	3.41	3.30	...	2600
A107	1.74	1.75	6.9	100
Pala Mine, So. California	1.77	1.70	7.0	104
Mean value	1.76	1.72	...	102
B.1	1.15	1.17	118	2530
Hombola, Tanganyika, collected 9/11/51	1.16	1.14	118	2600
		1.14	120	2640
		1.15	118	2570
Mean value	1.16	1.15		2580
B2.	2.35	2.36	242	2560
Zati (near) Hombola, Tanganyika, collected 24/7/52	2.38	2.36	236	2501
Mean value	2.37	2.36		2530

TABLE 5 – *Comparative lead determinations*

Sample type	Composition	Lead		
		Chemical value	Conventional polarographic value	Square wave polarographic value
		pct	pct	pct
Monazite, NBS 2601	ThO_2, 9.65; U_3O_8, 0.38; remainder rare earth oxides and phosphates	0.23	0.225	0.25 (±0.006)
Monazite, CRL, 181/54	ThO_2, 10.38; U_3O_8, 0.17	0.26	...	0.237 (±0.007)
Monazite, CRL 398/53	ThO_2, 6.04; U_3O_8, 0.23	0.17	...	0.19 (±0.005)
Monazite, CRL 399/53	ThO_2, 5.24; U_3O_8, 0.18	...	0.22	0.24 (±0.005)
Monazite, (ebonite)	...	...	0.22	0.22 (±0.003)

Schumacher ($4.8 \pm 0.4 \times 10^9$ for $T_{\frac{1}{2}} = 5.0 \times 10^{10}$) and this work extends his method to achondrites with a lower strontium content, the total quantity of strontium extracted from the Johnstown meteorite for these determinations was less than 5 μgm.

Lepidolites—The results found by isotope dilution for four lepidolites, and the rubidium analyses made previously by neutron activation analysis [*Cabell* and *Smales*, 1957] are listed in Table 4.

With the exception of the Johnstown meteorite (Table 2) there is good agreement between the rubidium analyses made by the two techniques, isotope dilution and neutron activation analysis, and it is reassuring to have the isotope dilution work supported by such an independent method of analysis. For the Johnstown meteorite the weight of sample used for each activation determination was of the order of 200 mgm so that the quantity of rubidium involved was close to the detection limit of the activation method for the neutron flux available at that time.

The ages found for Bikita Quarry and Pala Mine agree well with those reported by *Aldrich*, *Wetherill*, and *Davis* [1956], that is 2640 and 110 million years respectively.

The Determination of Lead in Monazites by Direct Polarographic Analysis

One other aspect of some Harwell analytical work with possible important application in geochronology is the development of a new direct polarographic determination of total lead in very small samples of monazite [*Milner* and *Slee* 1957].

The conventional polarographic method [*Smales*, 1948] requires a chemical separation of the lead, and a single determination may take as long as two days. By using orthophosphoric acid as a base electrolyte with the square wave polarograph, this time may be reduced to two hours.

After a preliminary attack with a mixture of nitric and hydrofluoric acids, the sample is dissolved in hot phosphoric acid, the solution diluted, and an aliquot used directly for a determination with the polarograph. Some results obtained in this way are recorded in Table 5.

These results show that lead concentrations of the order of 0.2 pct may be determined with a precision of two to three per cent for samples as small as ten mgm.

Acknowledgments—We wish to thank Brian H. Mason, American Museum of Natural History, New York, N. Y., who supplied the samples of meteorites; H. Bassett, who collected the lepidolites from Tanganyika; L. H. Ahrens, Department of Chemistry, University of Cape Town, who supplied the lepidolites from Bikita Quarry and Pala Mine; and in particular G. H. Palmer, Mass Spectrometry Group, Harwell, for his advice and assistance with our own mass spectrometer, and for enabling us to use his MS5 machine.

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Investigations in A^{40}/K^{40} Dating

S. S. Goldich, H. Baadsgaard, and A. O. Nier

Abstract—A number of potassium-bearing minerals and rocks have been studied with reference to their potential use in geochronology. The A^{40}/K^{40} ratios of cogenetic mica and feldspar were investigated, and in a group of unaltered granites and granitic gneisses ranging in age from 500 to 2500 m y, the feldspars commonly show an argon deficiency of 35 pct compared to the micas. Thermal alteration of granite, however, may affect biotite to a greater degree than the associated feldspar, and in areas where thermal history subsequent to the initial crystallization is supected, dating of both feldspar and mica may be particularly useful. Replicate determinations on crushed feldspar (40–60 mesh) showed no measureable leakage of argon over a period of 4–12 months. Stilpnomelane samples proved to be useless for dating. A series of samples representing progressive metamorphism from slate to phyllite to schist to coarse gneiss gave concordant A^{40}/K^{40} ages, and fine-grained sericitic materials have been used to advantage for dating an orogeny in central Minnesota.

Introduction

Development of the A^{40}/K^{40} dating method through the work of a number of laboratories in the United States and Canada has made this technique a valuable geologic tool. A great advantage of the A^{40}/K^{40} method lies in the widespread occurrence of potassium-bearing minerals and rocks. The writers are presently engaged in a project to date a large number of samples from the Lake Superior region, and in connection with this study some attention has been given to various potassium-bearing minerals and rocks which are potentially useful for A^{40}/K^{40} dating.

Investigations of Potassium-Bearing Minerals and Rocks

Cogenetic mica-feldspar pairs—Attention directed toward potassium feldspar for A^{40}/K^{40} dating purposes [*Wetherill*, *Aldrich*, and *Davis*, 1955; *Folinsbee*, *Lipson*, and *Reynolds*, 1956] has shown that cogenetic mica and feldspar, as a rule, do not give the same A^{40}/K^{40} ratios, that of the feldspar generally being appreciably lower. Many rocks, however, contain K-feldspar but little or no mica, so that further study of the discrepancy between the ages for the cogenetic pairs is desirable. Most of the published data represent mica-feldspar pairs from pegmatites. To supplement these a number of pairs from granites and granitic gneisses were analysed in this investigation.

A^{40}/K^{40} ratios for mica-feldspar pairs from pegmatites are plotted in Figure 1. Twenty-seven pairs, representing 54 determinations by a number of investigators, are from the literature; one pair represents biotite and a microcline-perthite from a pegmatite at Kinmount, Minnesota (Table 1). A plot of ratios for 20 mica-feldspar pairs from granites and granitic gneisses is shown in Figure 2. Three of the pairs are taken from the literature; the remainder were analysed at Minnesota (see Table 1).

Biotite separations were made on crushed rock (40-60 mesh) with a Franz Isodynamic separator; K-feldspar was separated from the non-magnetic fraction with heavy liquids. The mineral separations are not all as clean as desired, and improved techniques are needed. The biotite samples from Babbitt and from a locality 2½ miles south of Ely, Minnesota (Samples 4 and 11, Table 1) contain considerable chlorite. The K-feldspars are microcline-perthite and microcline-microperthite, and in addition to the plagioclase of the intergrowths, the chief contaminant is quartz. The low potassium content of Sample 9 is due largely to admixed quartz.

In both Figures 1 and 2 there is considerable scattering of the points between the lines indicating a 35 pct argon deficiency for the feldspar and no argon deficiency ($A^{40}/K^{40}_{mica}/A^{40}/K^{40}_{feldspar} = 1$). The apparent greater scattering of the points in Figure 1 may simply reflect the larger number of analysed pairs and the greater number of investigators. In the diagram for granites and gneisses (Fig. 2), the line of 35-pct argon deficiency passes within five per cent of all but six points, and it is significant that only two points fall appreciably below the line indicating no argon deficiency for the feldspars. All other points in both figures fall essentially between the two lines, with a majority of the points grouped about the upper line.

The two anomalous points in Figure 2 represent mica-feldspar pairs taken from thermally altered

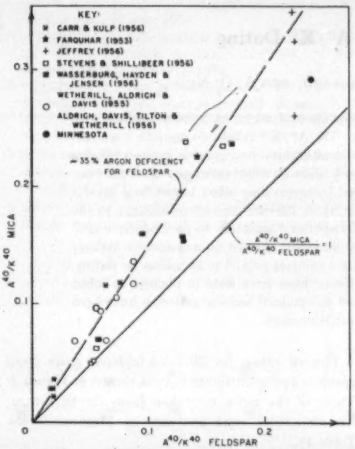

FIG. 1 – Plot of A^{40}/K^{40} ratios, mica-feldspar pairs from pegmatites

rocks. It is possible that other points in Figures 1 and 2 which fall below the line of 35-pct argon deficiency line may represent rocks with a thermal history subsequent to crystallization. For the present, however, an A^{40}/K^{40} ratio obtained for a feldspar must be considered to be a minimum value that may be as much as 35 pct too low compared with the cogenetic mica.

Dating of mica-feldspar pairs by the Sr-Rb method may throw light on this problem. As an initial check, Sr-Rb ages for three of the biotites included in Figure 2 have been obtained from the Massachusetts Institute of Technology through the courtesy of P. M. Hurley and are in good agreement with the A^{40}/K^{40} ages (Table 2).

Argon loss from crushed feldspar—Stevens and *Shillibeer* [1956] concluded that some feldspars may lose argon after being crushed and sampled. Replicate runs made at Minnesota on several feldspars, particularly the microcline from Dickinson County, Michigan, indicate no detectable argon loss from the crushed feldspar in as much as a year's time (see Table 3).

Stilpnomelane—Stilpnomelane, a potassium-iron-silicate, is widely distributed in the iron formations of Minnesota and other regions. Two analysed samples of well-crystallized stilpnomelane from the Cuyuna district contain essentially no argon, although they have 1.1 and 1.2 pct K.

TABLE 1 – *A^{40}/K^{40} determinations on mica-feldspar pairs*

Sample	Description	Mineral	K	A^{40}/K^{40}	Age × 10^{-9}
			pct		year
1	Rio de Janeiro	Biotite	7.11	0.0310	0.490
	Granite gneiss, KA-11	Feldspar	11.4	0.0251	0.405
2	Mellen, Wis.	Biotite	4.80	0.0778	1.05
	Granite, KA-93	Feldspar	10.6	0.0835	1.10
3	Waupaca, Wis.	Biotite	5.34	0.125	1.48
	Granite, KA-12	Feldspar	10.5	0.0717	0.98
4	Babbitt, Minn.	Biotite	3.50	0.0928	1.20
	Granite, KA-8	Feldspar	4.13	0.133	1.54
5	Piers, Minn.	Biotite	6.96	0.138	1.58
	Granite, KA-61	Feldspar	10.2	0.135	1.56
6	Snowbank Lake, Minn.	Biotite	7.00	0.0926	1.23
	Granite, KA-106	Feldspar	7.45	0.146	1.65
7	Rockville, Minn.	Biotite	6.24	0.152	1.69
	Granite, KA-6	Feldspar	9.08	0.0944	1.21
8	St. Cloud, Minn.	Biotite	5.04	0.176	1.87
	Gray granite, KA-10	Feldspar	10.6	0.112	1.37
9	Alberta, Canada	Biotite	7.33	0.204	2.03
	Granite core from Imp. Black Creek 10-27 (7328 feet), KA-20	Feldspar	0.92	0.135	1.55
10	Milbank, S. D.	Biotite	6.33	0.209	2.07
	Granite, KA-57	Feldspar	9.79	0.165	1.78
11	2½ mi. S. Ely, Minn.	Biotite	2.29	0.266	2.38
	Granite, KA-81	Feldspar	5.96	0.189	1.95
12	Echo, Minn.	Biotite	6.18	0.272	2.41
	Granite, KA-24	Feldspar	11.1	0.169	1.81
13	Sacred Heart, Minn.	Biotite	5.42	0.289	2.50
	Granite, KA-9	Feldspar	6.95	0.176	1.87
14	Sacred Heart, Minn.	Biotite	5.67	0.295	2.53
	Granite, KA-13	Feldspar	1.87	0.184	1.91
15	Kinmount, Minn.	Biotite	6.42	0.292	2.51
	Pegmatite, KA-4	Feldspar	10.6	0.239	2.24
16	Morton, Minn.	Biotite	5.45	0.299	2.55
	Granite gneiss, KA-15	Feldspar	6.49	0.237	2.23
17	Ridgely Twp., Minn.	Biotite	6.18	0.314	2.62
	Morton gneiss, KA-51	Feldspar	10.7	0.212	2.09
18	Morton, Minn.	Biotite	6.76	0.324	2.65
	Morton gneiss, KA-14	Feldspar	7.68	0.219	2.14

Constants: $\lambda_e = 0.557 \times 10^{-10}$/yr; $\lambda_\beta = 4.72 \times 10^{-10}$/yr.

Fine-grained metamorphic rocks—The Thomson formation of east-central Minnesota, ranging from slate to granitic gneiss, afforded an opportunity to test the A-K method on fine-grained materials. A series of six samples (Table 4) gives concordant dates. Biotite was separated from two samples of coarse-grained gneiss, and a partial concentration of mica was made of two samples of schist. A phyllite and the slate, however, were too fine grained to attempt concentration, and these samples were ground, sized to 40-60 mesh, and used directly. The average age for the six samples is 1.69 by, with a range from 1.64 to 1.73 by.

DISCUSSION

East Mesabi district—Although the loss of argon from mica by metamorphism may be regarded as a complication in A^{40}/K^{40} determinations, the dating of the mica-feldspar pairs from rocks for which

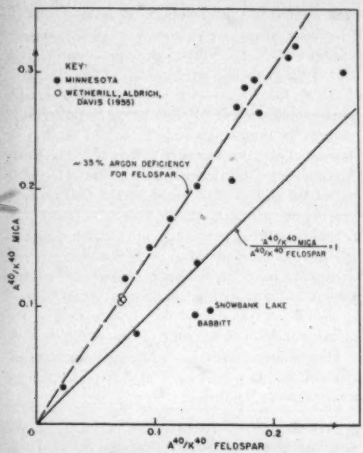

FIG. 2 – Plot of A^{40}/K^{40} ratios, mica-feldspar pairs from granites and granitic gneisses

TABLE 2 – *Comparison of A^{40}/K^{40} and Sr^{87}/Rb^{87} ages for Minnesota biotites*

Sample	Description	K	A^{40}/K^{40}	Age × 10^{-9}	
				A^{40}/K^{40} [a]	Sr^{87}/Rb^{87} [b]
		pct		year	year
5	Rockville, Minn. Granite, KA-6	6.24	0.154 0.151	1.71 1.68	1.65
6	St. Cloud, Minn. Gray granite, K-10	5.04	0.174 0.178	1.85 1.88	1.84
10	Sacred Heart, Minn. Granite, KA-13	5.67	0.293	2.53	2.35

Constants for K^{40}: $\lambda_e = 0.557 \times 10^{-10}$/yr; $\lambda_\beta = 4.72 \times 10^{-10}$/yr.
Constant for Rb^{87}: $\lambda_\beta = 1.39 \times 10^{-11}$/yr.
[a] Determined at Minnesota.
[b] Determined at Massachusetts Institute of Technology [*Pinson*, 1957].

TABLE 3 – *Argon leakage from crushed feldspar*

Sample	Description	K	A^{40}/K^{40}	Date
		pct		
...	Dickinson County, Mich. Microcline	9.79	0.0942	Mar. 3, 1956
			0.0955	July 2, 1956
			0.0950	July 18, 1956
			0.0960	Mar. 8, 1957
			0.0920	Mar. 22, 1957
1	Rio de Janeiro, Brazil Microcline-perthite	11.4	0.0244	June 10, 1956
			0.0260	Oct. 13, 1956
11	Kinmount, Minn. Microcline-perthite	10.6	0.232	June 17, 1956
			0.239	Jan. 13, 1957
13	Morton, Minn. Microcline-perthite	7.68	0.217	April 30, 1956
			0.221	July 9, 1956

TABLE 4 – *A^{40}/K^{40} dates on the metamorphic facies of the Thomson formation*

Sample	Rock type	K	A^{40}/K^{40}	Age × 10^{-9}
		pct		year
a	Slate near Thomson	3.00	0.147	1.66
b	Phyllite near Atkinson	1.04	0.156	1.72
			0.152	1.69
c	Schist at Barnum	4.27	0.155	1.71
d	Schist at Moose Lake	3.78	0.146	1.64
e	Gneiss near Denham	7.15	0.150	1.68
f	Gneiss near Denham	6.23	0.158	1.73
			0.157	1.73
			0.149	1.67

Average age = $1.69 \pm 0.03 \times 10^9$ years.
Constants: $\lambda_e = 0.557 \times 10^{-10}$/yr; $\lambda_\beta = 4.72 \times 10^{-10}$/yr.

a. Black slate from quarry, reservoir near Thomson, Minnesota, Cat. no. 35.

b. Phyllite, ½ mile west of Atkinson, Minnesota, Cat. no. 38.

c. Schist at railroad station in Barnum, Minnesota, Cat. no. 39.

d. Schist from cut along railroad just north of station in Moose Lake, Minnesota, Cat. no. 40.

e. Granite gneiss, 2½ miles west of Denham, Minnesota, from cut along Sault Ste. Marie Railroad, Cat. no. 41.

f. Granite gneiss, from outcrops in pasture 3 miles southwest of Denham, Minnesota, Cat. no. 43.

there is reason to suspect a thermal history subsequent to initial crystallization can be useful. Two such pairs are differentiated in Figure 2; one from Babbitt and the other from Snowbank Lake. Babbitt is in the East Mesabi district, and Snowbank Lake, approximately 30 miles to the northeast, lies roughly half way between the East Mesabi and Gunflint districts. In the country between Babbitt and the Gunflint district the Animikie iron formation has been cut out or engulfed by the Duluth gabbro intrusions. The iron formation has been extensively recrystallized by the gabbro, and apparently the granite also was affected.

The biotite from the Giants Range granite at Babbitt (Sample 4, Table 1) has been in large part altered to chlorite, and recrystallization has caused loss of argon, so that the A^{40}/K^{40} ratio is appreciably less than that of the associated feldspar. A similar relationship is noted for the mica-feldspar pair from the granite at Snowbank Lake. This sample (Sample 6, Table 1) comes from the south side of the lake and is only a few miles away from the gabbro. The dates of 1.20 by and 1.23 by

found for the biotite samples from granite at Babbitt and at Snowbank Lake probably date the time of intrusion of the gabbro in this region. This is supported by the date of 1.12 by obtained for biotite separated from a sample of core from a drill hole in the gabbro a few miles away from the granite outcrop at Babbitt.

The uncorrected feldspar ages for the granite samples are 1.54 by for Babbitt and 1.65 for Snowbank. If a minimum figure of 35 pct is accepted for argon deficiency in these feldspars, an apparent age of 2.1 by is obtained as an average. This figure is somewhat lower but approaches the 2.4 by age for biotite from the granite sample collected south of Ely, Minnesota (Sample 11, Table 1). All these samples are classified as Algoman by the Minnesota Geological Survey. The Snowbank Lake stock intrudes the Knife Lake sediments, and the Giants Range granite at Babbitt is overlain by the Animikie Biwabik iron formation.

Thomson formation—At the type locality, Thomson, Minnesota, the formation consists of interbedded slate, graywacke-slate, and graywacke. A few miles northeast of Thomson near Duluth the nearly vertical Thomson beds are overlain with angular unconformity by conglomerate and light-colored quartzite of the Puckwunge formation. These beds in turn are overlain by Keweenawan basalt flows. Tight folding has developed excellent slaty cleavage in the Thomson pelitic beds at the type locality and in adjacent areas; however, to the southwest the formation has undergone progressive metamorphism described by *Schwartz* [1942]. The change is most pronounced in the slates which give way to phyllites in the vicinity of Atkinson, Minnesota. Farther southwest at Barnum and Moose Lake, schist is developed, and at Denham, 35 miles southwest of Thomson, coarse-grained garnetiferous schist and granite gneiss are the high-grade metamorphic facies.

The correlation of the Thomson formation [*Grout, Gruner, Schwartz,* and *Thiel,* 1951] has always been uncertain. The formation was involved in folding dated in this study at approximately 1.7 billion years ago, precluding correlation with the Knife Lake slates based on the degree of metamorphism. The Knife Lake sediments were folded and intruded by granite (Algoman) at least 2.4 or more billion years old as discussed above. It should be emphasized that the A-K dates do not give the time of deposition but only the time of metamorphism. Work now in progress indicates that the Cuyuna iron formation of central Minnesota and iron formations in northern Wisconsin and in Michigan also were involved in this orogeny, approximately 1.7 billion years ago, marking the end of the Animikie or Huronian.

Rio de Janeiro granite gneiss—A second example of the application of A^{40}/K^{40} dating to problems in orogeny is that of the granite gneiss at Rio de Janeiro. This rock has been assigned to the Early Precambrian Mantiqueira series. The Cambrian age of 490 million years found for the biotite of the gneiss lends substance to *De Oliveira's* [1956, p. 8] prophecy. "What percentage of the area shown as epe on the Geologic Map of South America will eventually prove to be much younger is still unknown, but it probably will be substantial." Again it should be stated that the date is that of the orogeny and not of the time of deposition.

More detailed discussion of the geologic implications of the data presented in this paper will be undertaken in the future.

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Anomalous Leads from the Upper Great Lakes Region of Ontario

R. M. FARQUHAR AND R. D. RUSSELL

Abstract—We have previously reported on the presence of lead minerals of anomalous isotopic composition in the Sudbury, Ontario, mining area, and have used these anomalous isotope ratios in trying to determine the history and age of the Sudbury ores. We have since found a number of anomalous leads in the upper great lakes region of Ontario, some of which are more anomalous than the most anomalous Sudbury galenas.

As in the case of Sudbury, the anomalous leads vary enormously in isotopic composition even when closely related geographically. Leads found in the Thunder Bay region show extreme variation. There seems to be a correlation between isotopic composition and distance from the Lake Superior shore: those leads nearer the shore have generally large radiogenic components. Leads in the basement rocks some distance northwest of the lake are not apparently anomalous, having the isotopic constitution typical of the very old Keewatin leads.

It is calculated that the ratio Pb^{207}/Pb^{204} in the anomalous radiogenic component is 0.185 $\pm$ 0.005. From this it is deduced that the time of final mineralization of these leads is not greater than 1700 $\pm$ 30 m y ago and that the rocks from which the radiogenic lead was derived cannot be older than 2740 $\pm$ 40 m y.

Introduction—The isotopic composition of lead in lead ores has been the subject of extensive study during the past five or six years. Broadly speaking, the objects of such a study are two-fold. The first is an attempt to formulate an acceptable model to explain the broader features of the enormous variations known to exist in the isotope ratios of ore leads, with the hope that such a model will provide additional evidence regarding the geochemical process involving uranium, thorium, and lead during the evolution of the outer parts of the Earth [*Russell*, 1956ab]. The second is to determine something of the age and history of particular lead ore deposits. It is not the purpose of this paper to discuss the general problems of lead isotope behavior, but a brief statement of our views will serve as a suitable background for the particular discussion to follow.

In general, ore leads vary in isotopic composition in such a manner that younger leads have higher proportions of radiogenic lead 206, lead 207, and lead 208 while older leads are usually (but not always), poorer in these isotopes. For a great many leads there is a close correlation between the various isotope ratios and also between the isotope ratios and the supposed age of mineralization where this is known. These relationships are closely similar to those that would be expected for lead existing in a fixed environment of uranium and thorium from a common initial time to the various times of mineralization of the lead ores. Small but significant deviations from this picture have been pointed out [*Russell*, 1956ab] but are unimportant for the interpretations to be made in this paper.

There are some leads that have been referred to as anomalous which have isotope ratios that do not, at first sight, seem to participate in this regularity. We believe that additional amounts of radiogenic lead have been added to these leads, at or about the time of final mineralization. That is, an anomalous lead is simply an ordinary or non-anomalous lead which has been further altered. In view of this, the term 'anomalous' may be an unfortunate choice. It is noteworthy that this model for anomalous leads makes no provision for leads deficient in the radiogenic isotopes. It is principally in this regard that our model differs from that of *Houtermans* [1954].

On the basis of these considerations, it is obvious that ordinary leads may also be imperceptibly anomalous. However, it is important to have a criterion for leads that are significantly anomalous in those situations where the radiogenic additions are not sufficiently great to make the presence of anomalous leads immediately apparent. The criterion that we have found most useful is the constancy of the observed isotope ratios. In all cases for which we have data, anomalous leads from a particular region show variations in isotope ratios, while the ratios in ordinary leads remain remarkably constant. We have also used trace element composition as determined by the optical spectrograph as an aid in distinguishing anomalous and ordinary leads, but we have not used this technique for the leads reported in this paper.

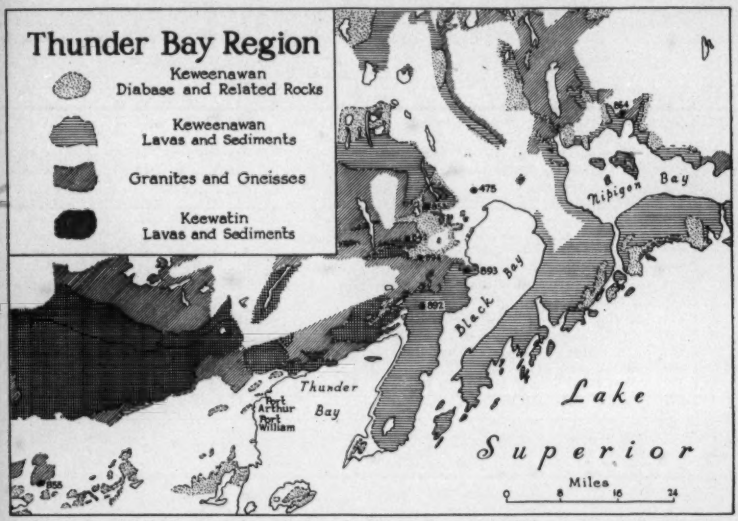

FIG. 1 – Geographical locations of samples from the Thunder Bay region which were isotopically analysed

In the course of our lead isotope studies, we have observed that anomalous leads from the Canadian shield lie within or are closely associated with rocks of the proterozoic type, while those occurring within Archean basement-type rocks are usually ordinary. For example, some of the leads from the Sudbury basin were extremely anomalous, and this important area lies within the Huronian sediments.

Thunder Bay region leads—The program of isotope analysis which commenced with the Sudbury galenas has been continued in an attempt to learn more about the ages and modes of deposition of the lead ores close to the boundary between the Keewatin and the Grenville geological provinces, with the added hope of throwing more light on the relationships between these two provinces and the Proterozoic-type sediments which overlie the Keewatin close to the boundary zone. Part of this investigation has consisted of the analyses of a number of galena samples from small lead deposits in the region between Lake Nipigon and Lake Superior, Ontario. The locations of the samples analysed are given in Figure 1, together with some pertinent geological features of the area.

The leads occur in normal fault zones cutting Keweenawan sediments and diabase sills. The mineralization apparently took place under low-pressure conditions and at moderately low temperatures as indicated by vugs still present in many of the breccia-filled faults and by the initial deposition of chert followed by coarser crystallization as amethystene quartz. It has been suggested [*Hawley*, 1929] that the ores have been concentrated from dolomitic sediments.

Table 1 gives the locations of the samples and the isotopic abundances found for each. Several of the samples have Pb^{206}/Pb^{204} and Pb^{208}/Pb^{204} ratios which are larger than those found for the most anomalous of the Sudbury galenas. It is obvious that these samples have had relatively large additions of radiogenic lead before being deposited at their present sites as lead minerals. In view of the geographical proximity of the samples, the large differences in isotopic composition must have been introduced by very local additions of radiogenic lead, a fact which has previously been noted also for the Sudbury galenas. At the same time it seems reasonable to assume that these deposits were all emplaced in a single episode of mineralization, and that they are consequently all of the same geological age.

A convincing arguement in favor of this simple

TABLE 1 – *Isotopic analyses of Thunder Bay galenas with analyses of some typical Keewatin galenas for comparison*

Sample	Location	Pb^{206}/Pb^{204}	Pb^{207}/Pb^{204}	Pb^{208}/Pb^{204}
	Keewatin galenas			
T-148	Newland Mine, Sioux Lookout, lat. 50°03′, long. 91°30′	13.66	14.78	33.46
T-149	Alcona Property, Sioux Lookout, lat. 50°03′, long. 91°30′	13.74	14.61	33.20
T-404	Steeprock Lake, lat. 48°47′, long. 91°38′	13.80	14.69	33.37
T-659	Geco Showing, Manitouwadge Lake, Ont., lat. 49°09′, long. 85°50′	13.37	14.59	33.38
T-852	Willroy Mines 2 zone, Manitouwadge Lake, Ont.	13.32	14.54	33.16
	Thunder Bay galenas			
T-853	Dorion Mine, Ont.	18.19	15.81	37.78
T-854	Ozone Mine, North of Kama Bay, north shore of Lake Superior, Ont.	18.32	15.89	37.14
T-475	Dorion, Ont., lat. 48°54′ long. 88°33′	18.55	15.95	37.82
T-642	Ogema property, lat. 48°40′, long. 88°50′	20.72	16.40	38.28
T-855	Silver Mountain, Lybster Twp., Ont.	30.05	18.26	41.17
T-894	Hilma Lake, McTavish Twp., Ont.	30.65	18.10	41.45
T-892	Near Pearl Station, McTavish Twp.	30.71	18.21	41.23
T-893	Caribou Mine, McTavish Twp., Ont.	33.88	18.69	43.98

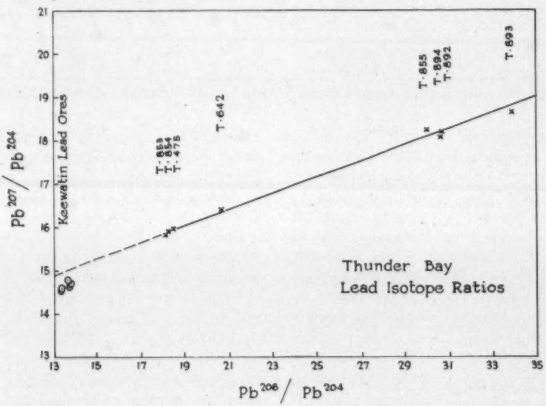

FIG. 2 – Relationship between the lead isotope abundances of the Thunder Bay ores (lead-207 vs lead-206)

picture is the regular way in which the variations in the Pb^{207}/Pb^{204} and Pb^{206}/Pb^{204} ratios are related. These ratios are plotted in Figure 2 together with the ratios for five galenas located in the Keewatin province some distance from the Grenville-Keewatin boundary, and remote from any Keweenawan cover rocks.

It is apparent that there is a close linear relationship between the Pb^{206}/Pb^{204} and Pb^{207}/Pb^{204} ratios in the Thunder Bay leads. It is clear from Figure 2 that the Keewatin leads do not participate in the linear relationship and therefore there is no isotopic evidence of any relationship between the Keewatin and Thunder Bay mineralizations. The linearity can be most reasonably explained if we assume that the Thunder Bay galenas are mixtures of different amounts of a single radiogenic lead and some ordinary lead. This reasoning is basically the same as that presented in interpreting the isotopic pattern of the anomalous Sudbury galenas [*Russell*

and others, 1954]. For the Sudbury leads, it was shown that the Pb^{207}/Pb^{206} ratio in the radiogenic component was given by the slope of the line of the graph of Pb^{207}/Pb^{204} against Pb^{206}/Pb^{204}. For the Thunder Bay leads, the slope of the line in Figure 2, and hence the ratio Pb^{207}/Pb^{206}, by a least squares calculation is 0.185 ± 0.005.

This ratio enables us to make certain limiting but useful statements concerning the age of deposition of the leads and the age of the rocks from which the radiogenic lead additions were derived. If the radiogenic component was generated in the interval between two times t_1 and t_2, then the ratio of the lead isotopes at time t_2 is given by

$$\frac{Pb^{207}}{Pb^{206}} = \frac{1}{137.8}\,\frac{(e^{\lambda' t_1} - e^{\lambda' t_2})}{(e^{\lambda t_1} - e^{\lambda t_2})}$$

where 137.8 is the present ratio of U^{238}/U^{235}, λ is the decay constant of U^{238} and λ' is the decay constant of U^{235}. Given a value of Pb^{207}/Pb^{206}, it is obviously not possible to define uniquely t_1 and t_2, but it is interesting to choose several values for t_1 or t_2 and compute the corresponding value of the other time parameter.

Setting t_2 at 0, (corresponding to a very recent mineralization) we calculate a value for t_1 of 2740 ± 40 m y, using the Pb^{207}/Pb^{206} ratio obtained above. This value of 2740 ± 40 m y is a maximum limit to the age of the rocks from which the radiogenic component of the leads was obtained.

A second calculation can be made by making the times t_1 and t_2 equal. In this limiting case the ratio of the lead isotopes is given by

$$\frac{Pb^{207}}{Pb^{206}} = \frac{1}{137.8}\,\frac{\lambda'}{\lambda}\,e^{(\lambda'-\lambda)t}$$

This is simply the ratio in which the lead isotopes were being produced from U^{238} and U^{235} at a time t years ago. For the Thunder Bay leads, the value of t is calculated to be 1700 ± 30 m y, which is an upper limit to the time at which the radiogenic lead in the anomalous galenas was separated from its source rocks. The deposition of these anomalous leads subsequent to the addition of radiogenic lead must therefore have occurred more recently than 1700 m y ago.

A lower limit on the age of the lead ores can, in principle, be obtained by assuming that the Thunder Bay samples with the lowest Pb^{206}/Pb^{204} and/or the lowest Pb^{208}/Pb^{204} have not received anomalous additions of that particular radiogenic lead isotope. Sample T-853 is poorest in Pb^{206} and T-854 is poorest in Pb^{208}. The dating equations recommended by Cumming [see, for example, *Wilson* and others, 1956, p. 328) are

$$t_{206} = 6.51 \times 10^9 \log_e \left\{\frac{29.82 - x}{11.02}\right\}$$

$$t_{208} = 20.04 \times 10^9 \log_e \left\{\frac{79.90 - z}{40.8}\right\}$$

where $x = Pb^{206}/Pb^{204}$ and $z = Pb^{208}/Pb^{204}$. For sample T-853 we find $t_{206} = 350$ m y and for sample

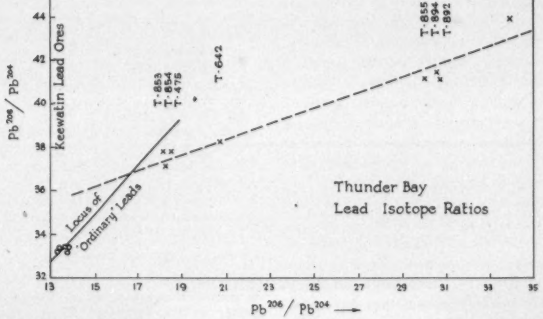

FIG. 3 – Relationship between the lead isotope abundances of the Thunder Bay ores (lead-208 vs lead-206)

T-854, t_{208} = 930 m y. Both results should be considered very approximate. Houtermans has also published formulas for dating galenas which give an age of 500 m y for sample T-853. Sample T-854 almost certainly has received anomalous additions of uranium lead and therefore cannot be dated by Houterman's method. If these two samples are also significantly anomalous in all isotopes, as seems most likely, the ages calculated would be too young. Therefore it seems rather unlikely that the Thunder Bay samples are younger than Precambrian.

It is of interest to plot Pb^{208}/Pb^{204} against Pb^{206}/Pb^{204} for the Thunder Bay leads. As can be seen in Figure 3, these ratios vary in a much less regular way than the plot of Pb^{207}/Pb^{204} against Pb^{206}/Pb^{204} shown in Figure 2. This irregularity can be taken as indirect evidence that the radiogenic component in the anomalous leads has been extracted on a local scale from rocks and minerals in which the uranium and thorium are distributed in a heterogeneous fashion because of their different chemical properties. Under such circumstances the amounts of Pb^{208} removed from the rocks would not be expected to bear any close relationship to the amounts of Pb^{206} and Pb^{207} extracted.

Although the points shown in Figure 3 do not lie closely on a straight line, as was the case for Figure 2, nevertheless a straight line can be drawn and its slope determined. The slope was found to be 0.37. Lead isotopes were being generated in this ratio 1700 m y ago by a mixture of 1.4 grams of thorium per gram of uranium. This value is less than half the value commonly accepted as the crustal average, and therefore suggests the possibility that the local rocks are enriched in uranium in preference to thorium. The calculated thorium to uranium ratio is very insensitive to the exact age relationships of the ores and the rocks from which the anomalous radiogenic additions were derived.

Summary and conclusion—The isotopic data obtained for these eight samples of galena from the Thunder Bay region of Ontario provide an example of the extent to which such studies by themselves may be useful in aiding our understanding of the times and processes of lead ore deposition. The analyses indicate that the leads of this region are of the anomalous type which have received significant additions of radiogenic lead before being deposited in their present locations. Since the leads have been deposited at low temperatures and form relatively small, separate deposits they have probably had ample opportunity to receive such additions in migrating through nearby rocks. The data suggests that all the leads sampled were deposited at about the same time. It is possible to place an accurate upper limit of 2740 ± 40 m y on the age of the rocks from which the radiogenic component of the anomalous leads was derived, and an upper limit of 1700 ± 30 m y to the time of deposition of the leads themselves. It is much more difficult to put a lower limit on the age of the Thunder Bay lead ores, because we do not know the isotope ratios of the ordinary lead to which the anomalous radiogenic additions were added. However attempts at dating the least anomalous leads suggest that they are probably not younger than Precambrian. The anomalous component of radiogenic lead was derived from a source that would have at the present a thorium to uranium ratio of only 1:4.

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Isotopic Analyses of Leads from Broken Hill, Australia

R. D. RUSSELL AND R. M. FARQUHAR

with

Spectrographic Analyses

J. E. HAWLEY

Abstract—This paper presents the results of isotopic analyses of 25 leads extracted from galenas from Broken Hill, New South Wales, Australia, and analysed at the University of Toronto. Some of the galenas occurred in conformable ore deposits of the Broken Hill type and some occurred in weak, gently dipping fractures and are of the Thackaringa type. We interpret the isotopic analyses as indicating that the conformable ores are ordinary leads and the Thackaringa ores are anomalous leads, that the probable age of the ordinary leads is about 1500 ± 150 m y, that the Thackaringa leads were derived from the conformable ores in a process that involved the addition of anomalous proportions of radiogenic lead from the country rocks, and that the addition of the anomalous radiogenic component occurred a few hundred million years after the time of formation of the conformable ores.

Qualitative spectographic analyses of some of the ores were carried out at Queen's University, Ontario, and are included in the paper. Most significant is the fact that the anomalous leads are distinguishable from the ordinary leads on the basis of trace element content. The significance of the spectrochemical analyses is discussed.

The Broken Hill lead deposits—The lead mines of Broken Hill, New South Wales, rank among the foremost producers of lead in the world. Since the first discovery of silver-lead ore 80 years ago, the development of the Broken Hill area has been accompanied by extensive studies of the geology and mineralogy of the area [*King* and *Thomson*, 1953; *King* and *O'Driscoll*, 1953]. The nature of these deposits, and the detailed descriptions of them that exist make them ideal for testing the methods that have been developed for applying common lead isotope analyses to the determination of ages and relationships of lead ores. We were therefore very fortunate when Haddon F. King, Chief Geologist of the Consolidated Zinc Proprietary, Ltd., took an interest in this problem, supplying us with a valuable suite of samples and assisting in assessing the geological implications of our findings.

The galena occurrences in the Broken Hill district are of two principal types. One type is exemplified by the main lode at the city of Broken Hill, and has therefore been called the Broken Hill type. A diagram of the main lode is shown in Figure 1, which is a representative cross section. The lead ore occurs as three lenses numbered in order from the surface; lead is also found in lesser amounts in the zinc lode and between the lenses. The lenses behave as perfectly conformable rock types and it has been suggested that they have shared the metamorphism and folding of the adjoining sediments. The associated rocks are highly metamorphosed and often include siliceous garnet rocks, garnet quartzites and garnet sandstones. The galena ore is associated with calcite, fluorite, manganese silicates, pyroxene, blue or opalescent quartz, green feldspar, and gahnite. Outlying deposits of the Broken Hill type contain more or less of the same associated minerals, and are otherwise similar to the main lode. All are of a conformable type and lie below a horizon formed of granitized gneiss named the Hanging Wall granite. Figure 2 is a highly idealized cross section of the Broken Hill mining area which shows the relationship between the Broken Hill-type deposits.

The second principal ore type has been called the Thackaringa type because early examples were found near the Thackaringa fault zone. Deposits of this type occur along weak, gently-dipping fractures, a fact which has been taken as indicating a mode of formation at shallower depths and lower temperatures than in the case of the Broken Hill type [*King* and *Thomson*, 1953]. Some of these ores occur in veins in places showing some banding and development of quartz crystals. The galena is coarse grained in a gangue of coarse-grained to very coarse-grained siderite with quartz. There is no garnet, blue quartz or gahnite, and sphalerite is uncommon. The Thackaringa-type ores are rich in silver,

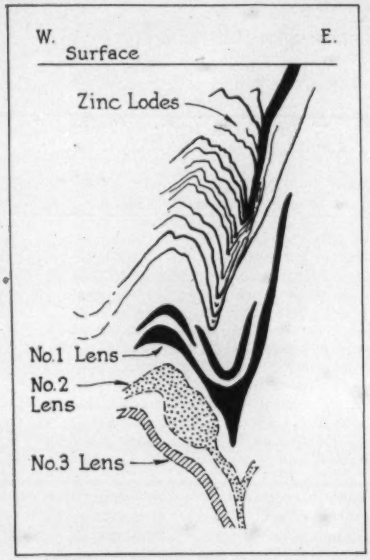

FIG. 1 – Representative cross section across the main lode at Broken Hill

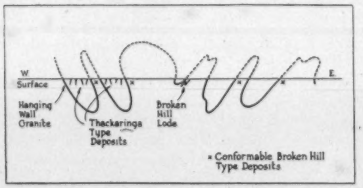

FIG. 2 – Idealized cross section of the Broken Hill mining area showing general structural relationships between Broken Hill-type and Thackaringa-type mines

very rich in places, but zinc is sparse or absent. Figure 2 also shows schematically the relationship of the Thackaringa-type to the Broken Hill-type deposits.

The samples sent to us by Haddon King are described in Tables 1–3 and their locations are shown on the map in Figure 3. Samples numbered 667–672 are from the main lode; samples numbered 721–727 are of the Thackaringa type, while those numbered 911–922 are samples of outlying deposits of the Broken Hill type.

TABLE 1 – *Location of specimens from main lode, Broken Hill*

Sample	Location[a]
667	No. 3 lens
668	Between no. 2 and no. 3 lenses
669	No. 2 lens
670	Rhodonitic zinc lode
671	No. 1 lens
672	Siliceous zinc lode

[a] At lat. 31°57′S, long. 141°28′E.

TABLE 2 – *Location specimens of the Thackaringa-type ore*

Sample	Location	H. F. King's number	Latitude (south)	Longitude (east)
721	Mayflower	18073	31°39′	141°25′
722	Mount Robe	18074	31 37	141 36
723	Terrible Dick	18075	31 42	141 34
724	3000 ft S of Apollyon Mine	18076	31 46	141 35
725	Daydream	18077	32 07	141 34
726	Victory extended	18078	31 42	141 27
727	Pioneer (Thackaringa)	18079	32 01	141 47
911[a]	Claim on Miner's Lease 165 17 miles, W.S.W. of Broken Hill	17567	...	...

[a] Possibly an intermediate type between Thackaringa and Broken Hill types.

TABLE 3 – *Location of specimens of the conformable Broken Hill type*

Sample	Location	King's number	Latitude (south)	Longitude (east)
912	Little Broken Hill Mine	17546	32°02′	141°20′
913	Pinnacles Mine	17549	32 01	141 35
914	Rupee Mine	17564	31 54	141 21
915	Centennial Mine	17550	31 51	141 32
916	Parnell Mine	17566	31 48	141 30
917	Balaclava Mine	17565	32 04	141 33
918	Rising Sun Mine	17547	31 59	141 29
919	Great Western Mine	17552	31 52	141 31
920	Globe Mine	17563	31 54	141 25
921	White Leads Mine	17548	32 00	141 43
922	Nine Mile Mine	17551	31 51	141 30

Isotopic analyses—The 25 samples from the Broken Hill mines were analysed isotopically with a 180° glass mass spectrometer described in previous publications [for example, *Collins* and others, 1954]. The mass spectrometer incorporated a gas source and the samples were prepared and analysed as volatile lead tetramethyl. In addition, Samples 667–672 were also analysed with a metal 90° sector-type instrument (type MS-2) purchased from the Metropolitan Vickers Electrical Company, Manchester, England.

The preparation of lead tetramethyl followed

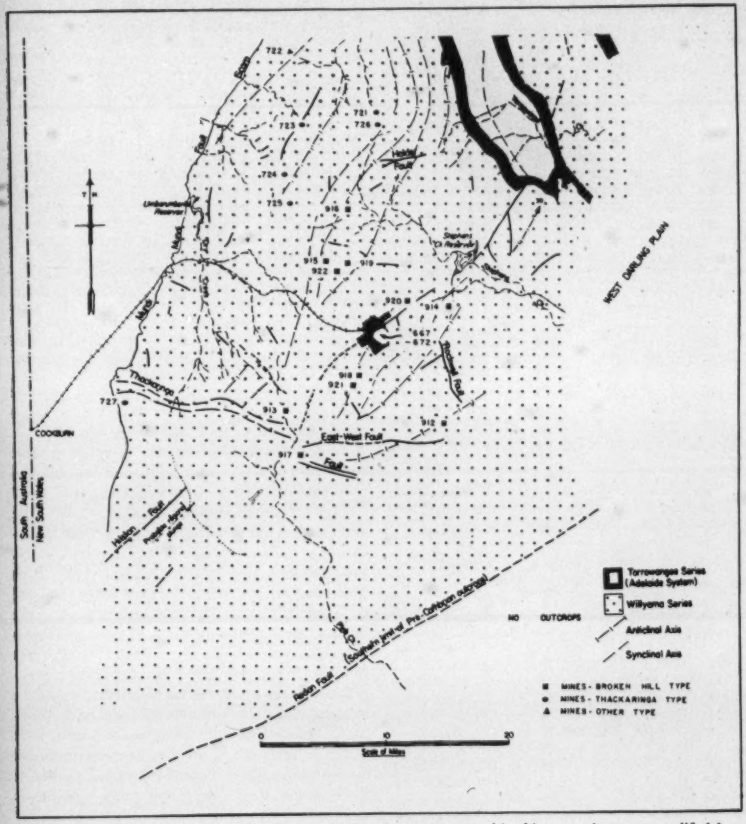

FIG. 3 – Geographical locations of samples for which analyses are reported in this paper; base map modified from that in *King* and *Thompson* [1953]

that previously outlined, but differed in that lead iodide rather than lead chloride was used to react with the methyl magnesium bromide reagent and that isoamyl ether rather than diethyl ether was used as a solvent. The reaction was carried out in vacuum in the manner suggested by *Ducheylard* and others [1953]. These modifications resulted in larger yields and a purer sample for analysis in the mass spectrometer.

Table 4 shows analyses of the samples from the main Broken Hill lode and also the reproducibility possible with this procedure. It is apparent that the reproducibility obtained from the 180° instrument was better than that obtained with the commercial spectrometer, even though the resolution of the Metropolitan Vickers instrument was appreciably greater. A possible explanation is that we are not so familiar with the latter instrument, although we have also discovered small non-linearities in the recording circuits. The average value of

TABLE 4 – *Isotopic analyses of galenas from main Broken Hill lode*

Sample	206/204	207/204	208/204	(204/206) × 100		(206/206) × 100	(207/206) × 100	(208/206) × 100
Analyses made with 180° mass spectrometer								
667	16.15	15.61	35.98	6.19	(1)[a]	100	96.64	222.8
668	16.16	15.61	35.96	6.18	(6)	100	96.56	222.4
669	16.04	15.49	35.68	6.23	(3)	100	96.56	222.4
670	16.06	15.49	35.66	6.22	(5)	100	96.43	222.0
671	16.11	15.57	35.88	6.20	(8)	100	96.64	222.8
672	16.13	15.60	35.97	6.19	(8)	100	96.68	222.9
Mean	16.11	15.56	35.86	6.20	(7)	100	96.58	222.6
±	0.05	0.06	0.09	0.01	(9)	...	0.09	0.3
Analyses made with 90° mass spectrometer								
667	16.03	15.44	35.67	6.23	(7)	100	96.30	222.6
668	16.03	15.41	35.73	6.24	(0)	100	96.17	223.0
669	16.02	15.46	35.91	6.24	(0)	100	96.50	224.1
670	15.97	15.39	35.62	6.25	(8)	100	96.34	223.0
671	16.06	15.47	35.83	6.22	(6)	100	96.30	223.1
672	16.05	15.43	35.78	6.22	(9)	100	96.09	222.9
Mean	16.03	15.43	35.76	6.23	(8)	100	96.28	223.1
±	0.03	0.03	0.11	0.01	(3)	...	0.20	0.5

[a] Ratio was found to be 6.191, but the last digit is uncertain, indicated here and elsewhere in Tables 4, 5, and 6 by parentheses.

TABLE 5 – *Isotopic analyses of samples from Thackaringa-type deposits*

Sample	206/204	207/204	208/204	(204/206) × 100		(206/206) × 100	(207/206) × 100	(208/206) × 100
721	17.91	15.81	38.60	5.58	(3)	100	88.29	215.5
722	19.48	15.91	39.41	5.13	(4)	100	81.70	202.3
723	18.06	15.83	38.94	5.53	(6)	100	87.61	215.6
724	18.09	15.83	38.94	5.52	(9)	100	87.50	215.3
725	17.91	15.78	38.79	5.58	(5)	100	88.10	216.6
726	18.07	15.88	38.97	5.53	(4)	100	87.85	215.7
727	17.42	15.65	38.12	5.74	(0)	100	89.85	218.8
911[a]	17.37	15.78	38.32	5.75	(7)	100	90.82	220.6

[a] Possibly an intermediate type between Thackaringa and Broken Hill types.

the runs from each instrument are very similar. It should be mentioned that all the analyses reported in this paper have been calculated from recently remeasured values which are considerably more accurate than those we have been using hitherto. The net result is that the lead-204 abundances that we are now reporting are approximately one-half per cent greater than the values reported for some Broken Hill samples in a previous publication [*Russell* and *Farquhar*, in press]. The Pb^{204}, Pb^{207}, and Pb^{208} abundances remain unchanged.

TABLE 6 – *Isotopic analyses of samples from conformable Broken Hill-type deposits; analyses from 180° mass spectrometer*

Sample	206/204	207/204	208/204	(204/206) × 100		(206/206) × 100	(207/206) × 100	(208/206) × 100
912	16.18	15.56	35.89	6.17	(7)	100	96.14	221.8
913	16.18	15.58	35.92	6.17	(6)	100	96.26	222.0
914	16.17	15.59	35.90	6.18	(4)	100	96.39	221.9
915	16.17	15.58	36.00	6.18	(4)	100	96.30	222.6
916	16.25	15.69	36.06	6.15	(4)	100	96.56	221.9
917	16.16	15.64	35.92	6.18	(8)	100	96.73	222.2
918	16.14	15.61	35.85	6.19	(2)	100	96.73	222.1
919	16.09	15.53	36.00	6.21	(3)	100	96.55	223.8
920	16.18	15.65	35.92	6.18	(3)	100	96.73	222.0
921	16.10	15.49	35.49	6.21	(1)	100	96.23	220.5
922	16.25	15.69	35.91	6.15	(7)	100	96.57	220.1
Mean	16.17	15.60	35.90	6.18	(3)	100	96.47	222.0
±	0.05	0.06	0.15	...		...	0.21	0.08

Table 5 shows the analyses of samples from the other conformable ores which have isotope ratios almost identical with the main lode.

Table 6 shows the analyses of samples from the deposits of the Thackaringa type. These samples presented difficulties in analysis because of small amounts of contamination at masses 204, 205, 249, and 250, and others at higher masses. Since hydrocarbons of these masses would have been easily resolved from the lead-tetramethyl peaks, it is probable that the contaminating peaks involved compounds of some heavy element present in the original galenas, although it is extremely difficult to imagine a suitable compound that would persist through the highly selective lead tetramethyl preparation. Fortunately the contamination could be recognized and could be avoided by careful chemical manipulations. All contaminated runs were discarded and none of the measurements recorded involves any correction for background peaks. As a precaution all samples of this group were run in duplicate.

Interpretations of the isotopic analyses—The principles for interpreting common lead isotope ratios were laid down by *Holmes* [1946], and extended by *Russell* and others [1954] and *Houtermans* [1954]. Applications to the particular problems of sulphide ore deposits have been discussed by *Russell* and *Farquhar* [in press]. The methods and interpretations of the latter authors are adopted here; namely, the leads have grown in the upper mantle in a generally homogeneous lead-uranium-thorium environment, have been brought to the surface during periods of orogeny, and in some cases have received anomalous additions of

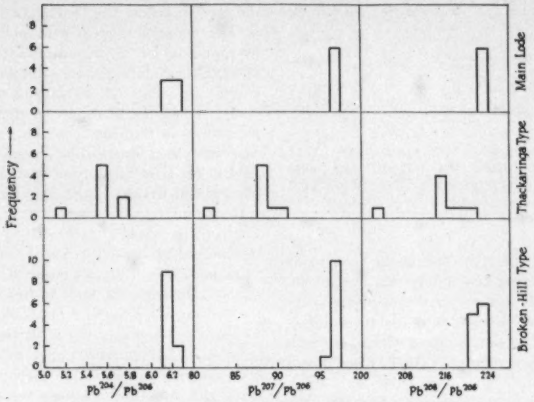

FIG. 4 – Histogram of isotopic analyses of Broken Hill galenas

radiogenic lead from surface rocks. We define 'ordinary' those leads to which the anomalous additions are very small or zero.

Figure 4 shows histograms of the Pb^{204}/Pb^{206}, Pb^{207}/Pb^{206}, and Pb^{208}/Pb^{206} ratios corresponding to the analyses shown in Tables 4, 5, and 6. This figure leaves no doubt that the lead ratios of all the Broken Hill-type ores tested are identical within the accuracy of the measurements, and that they are identical with ores from the main lode at the city of Broken Hill. It also shows clearly that the lead isotope ratios of the Thackaringa-type ores are distinctly different. This is a similar phenomenon to that observed in the leads at Sudbury, Ontario, and the Tri-State mining regions of the United States, which also show variations of lead isotope ratios within each deposit [*Farquhar* and *Cumming*, 1954].

In the cases of Tri-State and Sudbury, which have been thoroughly studied, there is no doubt that the lead ores contain anomalous proportions of radiogenic lead probably extracted from surface rocks during the processes by which the lead minerals were concentrated and deposited. The Broken Hill analyses, reported here, are not such clear-cut examples of anomalous leads because they all have isotope ratios which could be those of ordinary leads. There are, however, two reasons for supposing that the Thackaringa-type ores are anomalous. The first is that the supposition that all Broken Hill leads are ordinary would require that there were two major periods of primary mineralization of the Broken Hill area separated by a period of time of the order of 1000 m y, and that there was little or no mixing of the two leads at the time of the second mineralization. While not impossible, this seems to us to be a less attractive possibility than a single major mineralization perhaps with subsequent resolution and redeposition of part of the lead ores. The second reason, which is probably more important, is that the abundances plotted in Figure 4 show a considerable spread in the ratios for the Thackaringa-type minerals. Variations in lead isotope ratios have been shown to be generally characteristic of the anomalous leads [*Russell* and *Farquhar*, in press]. Neither of these reasons is conclusive, but in the absence of any other information we will assume that the Thackaringa ores are anomalous. The conformable-type ores, on the other hand, show no abundance variations and we will assume that they are ordinary, since there is no evidence to the contrary.

Our interpretation of these isotope ratios is that the conformable Broken Hill ore layer was the first to be deposited. We assume it to be formed of ordinary lead having ratios we would expect to find in lead arriving from a rather homogeneous mantle. Therefore the process of mineralization permitted little or no anomalous additions either because these processes were rapid and simple, allowing a minimum of association of the lead with the country rocks, or that the associated country rocks were not sufficiently radioactive or sufficiently old to contribute significant amounts of radiogenic

TABLE 7 – *'Galena ages' calculated from mean isotope ratios*

Sample	Mass spectrometer	Houtermans's curves		Cumming's equations		
		Age	U^{238}/Pb^{204}	T_{206}	T_{208}	Mean age
		m y		m y	m y	m y
667–672	180°	1730	9.8	1420	1533	1470
667–672	90°	1680	9.7	1450	1580	1520
912–922	180°	1720	9.4	1400	1520	1460

[a] Extrapolated to present.

lead. At some later time part of the conformable lead was dissolved and was carried upward and concentrated in fissures in the overlying rocks. This migration of the lead permitted its close association with the overlying rocks which are known to be abnormally radioactive (H. F. King, private communication).

On the basis of the foregoing interpretation of the observed isotope ratios, it is possible to make numerical calculations of the age of deposition of the Broken Hill type ores. By the method described by *Houtermans* [1953], and with the mean isotope ratios for the sets of samples from the main lode (667–672) and the conformable deposits (912–922), the results given in Table 7 have been obtained. These age values are calculated from the ratios Pb^{206}/Pb^{204} and Pb^{207}/Pb^{204}. By this method it is also possible to determine the present U^{238}/Pb^{204} ratio for the source from which these leads were derived. This ratio has also been tabulated in Table 7.

With the method suggested by *Russell* and others, [1954] and the lead isotope abundance-time curves derived by Cumming [see, *Wilson* and others, 1956], a second calculation of age can be made, based on the Pb^{206}/Pb^{204} and Pb^{208}/Pb^{204} ratios. The ages for each set of samples have been tabulated together with the mean values in Table 7. In the calculations by Houtermans' method and Russell's method the analyses made on the 180° mass spectrometer and the 90° mass spectrometer have been performed separately, and give some indication of the extent to which different mass spectrometers may affect the ages determined from lead isotope ratios. In view of the similarity of the mean isotopic ratios for the main lode samples and the conformable type samples, no significant difference in the age of these deposits would be expected. There is a significant difference between the age values calculated by Houtermans' method and by the method of Russell and others. This apparent difference is believed to be due partly to a failure of the assumption (basic to both methods) that the lead ores are derived from a homogeneous source in which the uranium/lead and thorium/lead ratios change with time only as a result of radioactive decay, and partly to the use of slightly different parameters in the equations. The basic assumptions have been discussed by *Russell* [1956] in the light of the large quantity of isotopic data which has accumulated in the past few years.

Geological evidence cannot at present suggest whether the average of 1480×10^6 years given by the method of Russell is more correct than the value of 1780×10^6 years given by Houtermans' method. However, the leads at Broken Hill lie in the Willyama series which are somewhat similar to those in which also occur in the radioactive minerals at Radium Hill, eighty miles away. We have analysed isotopically a specimen from Radium Hill with the following results (Toronto Sample 29).

Date of analyses	Pb^{204}	Pb^{206}	Pb^{207}	Pb^{208}
July 24, 1951	0.21 (7)	79.01	10.33	10.43
Sep. 28, 1951	0.21	79.70	10.34	10.78

We calculate lead ratio ages of 1490 m y and 1530 m y corresponding to these two analyses of this sample. While we do not consider that this determination necessarily dates the Broken Hill galenas the agreement between it, the ages obtained by Cumming's equations, and the limits on the age of the anomalous leads derived below is very striking. A further reason for prefering the ages obtained from Cumming's equations is that they give ages for Sudbury, Ontario, galenas which are in excellent agreement with some potassium argon, and rubidium-strontium ages, while the ages obtained by Houtermans' method are again substantially higher.

On the assumption that the satellite deposits consist of lead derived from the main lode which has been further contaminated with radiogenic lead from the surrounding rocks, an upper limit may be placed on the time at which this mineralization took place. If the data for the satellite deposits are combined with the results for the samples from the main ore body, the ratio of Pb^{207}/Pb^{206} in the radiogenic component can be determined from a least-squares calculation. This method has been described by *Russell* and others [1954], as applied to the galena samples from the Sudbury, Ontario, area. For the deposits in the

Broken Hill area, this ratio of radiogenic Pb^{207}/Pb^{206} is 0.110 ± 0.015. These isotopes were being produced in this proportion at a time (1020 ± 150) m y ago. This figure then represents an upper limit to the age of the satellite ore bodies, since the ores must have been altered isotopically at least as recently as 1020 ± 150 m y ago.

It is also possible to place an upper limit on the age of the rocks from which the anomalous radiogenic lead component of the galenas was derived. This is done by postulating that the time of emplacement of the Thackaringa-type ores cannot be smaller than zero (that is, the present), and that at the time of emplacement of the leads, anomalous lead was added from old country rocks. The age of the country rocks is then given in terms of the isotopic composition of the radiogenic lead by the well known formula used in the radiogenic lead-lead age determination methods; namely

$$\frac{Pb^{207}}{Pb^{206}} = \frac{1}{137.8}\left\{\frac{e^{\lambda_{207}t} - 1}{e^{\lambda_{206}t} - 1}\right\}$$

where t is in millions of years. The age so calculated for the Broken Hill leads is 1830 ± 40 m y. If the Thackaringa leads are older than zero years, this figure would be lowered. Therefore, the rocks supplying the anomalous radiogenic component to these ores cannot be older than 1830 ± 40 m y.

Spectrochemical analyses—Qualitative spectrochemical analyses were made at Queen's University, Kingston, Ontario, on hand-picked galenas 667–672, 721–723, and 725–727. A pure galena concentrate of 724 could not be made even under the binocular microscope, because of its fine grain and admixture with other minerals. The mineralogical purity of the analyzed samples was probably somewhat variable, as suggested by the determinations of zinc, silicon, aluminum calcium and magnesium. The analyst was G. MacDonald.

Samples were finely ground and analyzed by d c arc methods under the following conditions:

Instruments, Two-meter grating spectrograph, Applied Research multi-source power unit; time, 60 sec; amperage, 7; transmission, 100 pct; grating doors, 0.7; slit, 30; gap, 3 mm; electrodes, special high-purity graphite, center-post crater electrodes, 0.24 inch diameter; grating, 24,400 lines per inch; film, Eastman Spectrum Analysis 1.

Films were developed by standard procedure and the density of lines as estimated on a comparator-densitometer as shown by Table 8.

Results—The results are given in Table 8. In addition to those elements listed the following were sought but not found: B, Ba, Be, Co, Ga, Ge, Hf, In, Lu, Mo, Sc, Y, Zr.

Elements detected include most of those found in various galenas, as summarized by *Fleischer* [1955]. Minerals associated with the galena in the main Broken Hill lodes, according to descriptions by *Stillwell* [1953] include at least twelve species containing antimony, four with silver, chiefly in tetrahedrite and dyscrasite, two with cobalt, and one or more with nickel, and possibly two, (stannite and cassiterite) with tin. No bismuth species is mentioned.

In the two groups of galenas studied, that is, Samples 667–672 (ordinary leads) and Samples 721–727 (anomalous leads), no outstanding chemical differences are apparent in content of Ag, Mn, and Fe, nor in probable impurities of Si, Al, Mg, and Ca. A very distinct difference between the two groups, however, is the presence in the first of bismuth and tin and the absence in the second of detectable amounts of these elements.

Averaging the samples in each group also shows the occurrence of more cadmium, zinc, thallium, antimony, and vanadium in the first group and less in the second. Copper appears more abundant in the second group as does nickel which was not detected at all in the first.

In the first group of samples a comparison of Ag 3382.9, Bi 3067.7, Sn 2840.0, and Sb 2598.1 shows no very marked difference in the lines. This may indicate the rather uniform presence in the galena of compounds containing these elements or fairly uniform solid solution of them in the galena.

In the second group, however, though silver remains about the same as in the first group, antimony is relatively lower and bismuth and tin are virtually absent. This behavior is different from that noted by *Tischendorf* [1955], as summarized by *Fleischer* [1955] who notes "that bismuth varied with the content of silver and antimony, all decreasing with decreasing temperature of formation."

Note should also be made that no correlation is apparent between the cadmium and zinc of both groups of samples, as would be expected if both were contained in sphalerite inclusions.

Significance of Spectrographic analyses—The above chemical differences in the two sets of samples, the one with ordinary leads, the other with anomalous leads, indicate some difference in their genetic history. Without much more detailed information of a similar nature on many more specimens of both the associated metallic and

TABLE 8 – *Results of spectrochemical galena analyses (by J. E. Hawley)*

Spectral line	Main ore body samples						Satellite ore body samples					
	667	668	669	670	671	672	721	722	723	725	726	727
Ag 3380.7	E	S	S	VS	S	S	S	E	VS	S	S	VS
Ag 3382.9	VS	S	S	S	S	VS	S	E	VS	S	S	VS
As 2780.2	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Bi 2898.0	FTR	W	TR	S	ND	W	ND	ND	ND	ND	ND	ND
Bi 2938.4	TR	W	TR	M	TR	W	ND	ND	ND	ND	ND	ND
Bi 3067.7	S	S	S	S	W	S	ND	ND	ND	ND	ND	ND
Cd 3252.5	S	S	S	S	S	S	TR	S	M	M	M	S
Cd 3403.6	W	W	M	W	W	M	ND	W	ND	ND	ND	W
Cu 3247.5	VS	S—	S	S	S	VS	S	E	S	VS	S	VS
Cu 3274.0	VS	S	VS	VS	VS	E	E	E	E	E	E	E
Ni 3414.7	ND	ND	ND	ND	ND	ND	ND	FTR	FTR	W	ND	ND
Tl 2767.9	TR	FTR	W	FTR	W	FTR	VFTR	VFTR	ND	ND	ND	ND
Sn 2840.0	S	M	S	S	M	S	ND	W	ND	ND	ND	ND
Sn 3175.1	S	M	S	S	M	S	ND	ND	ND	ND	ND	ND
Sb 2598.1	S	M	S	M	S	S	M	S	TR	TR	TR	S
Sb 3232.5	M	ND	M	TR	M	M	FTR	W	ND	ND	FTR	M
Sb 3267.5	M	TR	M	W	M	M	TR	M	TR	ND	TR	M
Ti 3372.8	TR	ND	ND	ND	ND	ND	TR	ND	TR	ND	ND	ND
V 4379.2	M	M	M	M	M	M	TR	W	W	W	W	S
Zn 3302.6	S	ND	ND	M	ND	VS	ND	ND	M	ND	ND	M
Zn 3345.0	VS	ND	ND	S—	ND	VS	ND	ND	S	ND	ND	S
Mn 2794.8	S	S	W	S	M	S	S	M	VS	TR	TR	M
Fe 2020.6	S	M	W	S	M	S	S	S	VS	M	M	S
Ca 3933.7	E	E	S	VS	VS	VS	S	E	VS	S	VS	VS
Si 2516.1	S	S	M	S	M	S	W	S	E	M	M	S
Mg 2852.1	S	S	S—	S	S	S	S	S	S	S	S	S
Al 3082.2	M	S	M	M	M	M	ND	ND	VS	M	M	S

ND, not detected; W, weak; VFTR, very faint trace; M, medium; FTR, faint trace; S, strong, TR, trace; E, extreme.

gangue minerals, and a firm opinion on the significance of the paragenesis of the ores, whether it represents primary deposition on the one hand or is the result of anamorphism or regeneration of previously formed deposits on the other, it is not possible to say with any certainty how these differences arose.

From a negative point of view, it seems unlikely that the more marked differences can be explained simply as due to decreasing P/T conditions of deposition from common ore fluids, in view of the persistence of silver even though antimony, bismuth, and tin are lower or missing in the second group. The same argument possibly may be advanced against the first group of galenas representing a primary deposition and the second a regenerated or reworked group of deposits formed at either elevated or especially, lower temperatures. Deposition at different times from a different or differentiating ore fluid is possible, but may be unlikely in view of isotopic differences reported herein. On the other hand, acquisition by galena or its source fluid of elements such as bismuth and tin from certain wall rocks or even earlier and locally deposited metallics by the one group, and of radiogenic lead by the other, seems a distinct possibility. Whether similar 'contamination' might result from anamorphism or regeneration at elevated temperatures of previously formed deposits in somewhat different host rocks is a question requiring further study.

Conclusions—In this paper we have reported both isotopic and spectrographic analyses of galena samples from Broken Hill, New South Wales. These analyses show a very clear correlation between trace-element composition and isotopic constitution of the lead, and in fact it would be quite possible to use the spectrographic analyses to distinguish between the anomalous (Thacharinga type) and ordinary (Broken Hill type) leads. This supports our previous suggestion [*Russell* and others, 1954; *Farquhar* and *Cumming*, 1954] that anomalous leads generally have experienced a different geochemical history than the ordinary leads. It seems possible that the application of trace element analyses as a criterion for anomalous leads could become of general importance.

Assuming that the ores of the Broken Hill type

are not anomalous their approximate ages are 1700 ± 100 m y by the method devised by *Houtermans* [1954] and 1500 ± 150 m y by the method preferred by the present authors [*Wilson* and others, 1956].

Assuming that the anomalous (Thackaringa-type) ores are mixtures of a single ordinary lead and a single radiogenic lead, we find the ratios of the isotopes in the radiogenic lead to be $Pb^{207}/Pb^{206} = 0.110 \pm 0.015$. This leads to a value of 1020 ± 150 m y for the upper limit to the age of the Thackaringa-type ores and a value of 1830 ± 40 m y for the upper limit to the age of the rocks from which the anomalous radiogenic lead component was derived.

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Reinterpretation of the Uranium-Helium Ages of Iron Meteorites

E. J. Öpik and S. F. Singer

Abstract—Measurements of uranium and helium content of iron meteorites have been carried on by Paneth and his collaborators over the last 25 years, but the interpretation of their measurements has varied widely. The purpose of the present note is to suggest a reinterpretation in the light of (1) our recent knowledge of the cosmic-ray effects on meteorites, and (2) the physical mechanism of meteorite creation.

Assumptions underlying the interpretation—The original estimates of meteorite ages ranged from values as low as 100,000 years up to 7 or 8 billion years [*Arrol* and others, 1942]. These were derived under the assumptions: (1) that all of the helium is produced by the decay of uranium (and thorium), and (2) that none of the helium had leaked out of the meteorite. Both of these assumptions are probably not justified and, as will be shown later, lead to a reinterpretation of these age determinations.

In the first place it was indicated [*Bauer*, 1947] that a large part of the helium would be produced in the disintegrations of iron nuclei by cosmic rays; over 30 pct of the helium so produced should be in the form of helium-3 [*Singer*, 1952]. This provides a convincing demonstration of its cosmic-ray origin since radiogenic helium must all be helium-4. Thus, by subtracting all of the cosmic-ray produced helium, one would be left with radiogenic helium only and could then recompute the ages. This approach has been taken [*Dalton* and others, 1953] but still with the retention of assumption (2), namely that none of the helium has leaked out. This procedure gives ages in the vicinity of 100 to 200 m y [*Dalton* and others, 1953] and these have been interpreted as the date of solidification of the iron mass, that is, preceding the breakup of the parent body into the actual meteorites [*Reasbeck* and *Mayne*, 1955].

This result seems very much in contradiction with presently accepted ideas concerning the formation of the protoplanets and concerning their solidification which must have followed very soon thereafter [*Kuiper*, 1954; *Urey*, 1955; *Allen* and *Jacobs*, 1956]; it is in disagreement also with the argon potassium age determinations [*Gerling* and *Pavlova*, 1951; *Wasserburg* and *Hayden*, 1955; *Thomson* and *Mayne*, 1955] and the lead-isotope determinations [*Patterson*, 1956], all of which indicate a solidification time of 4 to 4½ b y. Furthermore, it has been shown recently that the breakup ages of many of these meteorites, as deduced from their exposure to cosmic rays, is of the order of 200 to 300 m y [*Singer*, in press], Hence the assumption that the iron phase solidified 200 m y ago and that somehow the planet broke up immediately after solidification [*Reasbeck* and *Mayne*, 1955] seems *ad hoc* and is not based on any physical argument. Besides, the formation of the Widmanstätten pattern requires the iron to have cooled slowly (presumably in the interior of a planet) for a long period of time after solidification.

It is for these reasons that the second assumption, that is, retention of the radiogenic helium over long periods of time, has been questioned. In addition, the measurements themselves have been questioned, particularly the validity of the uranium determinations. *Reed* and *Turkevich* [1955] have shown by neutron activation techniques that there is practically no uranium in the iron phase of the meteorites. (However, an argument has been put forward to show that in the measurements of Paneth's group larger samples were used which might well have included impurities in which uranium is preferentially located [*Singer*, 1957]; the question of the actual uranium content of the meteorite samples which Paneth measured is still an open question. High values, of the order of 10^{-8} gm/gm, similar to Paneth's, have also been obtained by *Starik* and *Shats* [1956], while Reed and Turkevich, in a private communication, April, 1957, report 10^{-12} to 10^{-10} gm/gm for seven iron meteorite samples.)

We now turn our attention to the second assumption underlying the interpretation, namely that none of the helium has diffused out of the meteorite. This assumption seems to be backed up by an experiment performed on the meteorite Mt. Ayliff where samples were heated to high temperatures without loss of helium [*Paneth*, 1953]. However, it has been pointed out this meteorite contained mostly cosmic-ray helium and one would expect that cosmic-ray helium being produced within the crystal lattice would not leak out [*Singer*, 1954]. A crucial experiment to test this

point has been suggested [*Singer*, 1957] which would consist in heating a meteorite containing both cosmic-ray and radiogenic helium and looking for an increase of the He^3:He^4 ratio as a function of temperature.

Even if it should turn out that the higher uranium values are valid, we conclude that the hypothesis that the meteorites solidified 200 m y ago [*Dalton* and others, 1953] is untenable. There is, however, the interesting fact that the uranium-helium ages are fairly consistent among themselves, and the further fact that they are not far removed from the breakup ages deduced from cosmic ray exposure. This suggests, therefore, that the breakup may also have been responsible for the removal of radiogenic He^4 which had accumulated up to the time of breakup. One such mechanism which would definitely enhance the escape of He^4 is the heating of the meteorite in the process of breakup.

Physical processes in the creation of meteorites—The problem of collisional breakup of a planet is similar to that of formation of meteor craters (manuscript by Öpik, Meteor impact on a solid surface, 1957). The pressure in the shock wave decreases with the distance from the center of impact, and the degree of destruction varies accordingly. Whereas the portions nearest to the center are vaporized or pulverized, larger fragments are formed and ejected from near the periphery; these are to become meteorites. This description of the consequences of a collision remains valid even for subsonic velocities when the energy of vibration exceeds the limit set by the elastic properties of the material. The velocities of ejection are mostly small, a few hundred meters per second only, such as would be compatible with the capability of the material to resist shock; the fragments so ejected will move on orbits similar to those of the colliding bodies and, if these were asteroids, will be confined to the asteroidal region of space; they will not intersect the orbit of the Earth, and will not be observable as meteorites.

However, some fragments will be able to acquire higher velocities, of the order of the relative velocity of the collision, without being subject to excessive pressure; they will thus be able to retain their identity and crystal structure. For example, this could happen with fragments 'spalled' off the rear surface of the smaller of the two colliding bodies (Öpik manuscript cited); for a certain upper limit of size (ratio of fragment radius to planet radius) the fragments can be decelerated and backfired to space with velocities of several kilometers per second. The crushed and vaporized material of the smaller planet formed in front of the fragments acts as a brake and gives time for deceleration and subsequent acceleration, without leading to excessive pressures.

These fragments, few in number as compared to the total mass of crushed material, but numerous enough in comparison with meteorite frequency in near-terrestrial space, are probably the source of observable meteorites. A relative velocity of five km per sec would suffice to change an asteroidal orbit in such a manner as to bring the perihelion inside the Earth's orbit. The fragments may thus become meteorites observable from Earth.

Bodies crossing the orbit of the Earth, that is, which at some point of their orbit can be at the Earth's distance from the Sun, have a chance of collision with the Earth even when the two orbits are not intersecting. This is due to slow changes in the orbital elements, a precession of the orbital plane and an advance of the perihelion which are caused by planetary perturbations and which make intersection of the orbits possible at time intervals spaced tens or hundreds of thousands of years. The probabilities of collision, or the expectations of life, of asteroids or meteorites crossing the orbits of the Earth and other planets depend upon the orbital elements and have been calculated [*Öpik*, 1951]. Thus, the minor planets such as Apollo, Adonis, Hermes, and Icarus have expectations of life ranging from 40 to 170 m y, Encke's comet 270 m y, and the Geminid meteors 250 m y. All of these objects move on orbits which are completely inside Jupiter's orbit and are such as could be acquired by meteoric fragments. The average lifetime of these fragments, before they are swept up by Earth, Mars, Venus, or Mercury, can also be of the order of 100 m y. Each 100 m y their numbers would decrease in a ratio of about 3 to 1. It may be expected, therefore, that observable meteorites are mostly the result of recent collisions which happened a few hundred million years ago. Fragments of older collisions are mostly eliminated, having been absorbed by the sweeping action of the inner planets. This concept seems to fit well into the picture of cosmic-ray helium age determinations [*Singer*, in press]; six determinations up to date point concordantly to a catastrophe or catastrophes which happened as recently as only 300 m y ago.

Heating of meteorites at the time of breakup—We can now examine the thermal history of the meteorites in more detail. As a result of the collision, a very strong shock wave originates at the point of

contact of the two colliding bodies. This shock wave, while not sufficient to obliterate the crystal structure of the fragments which survive as meteorites, can produce considerable deformation and frictional heating. From this fact we can calculate approximately the temperature to which the meteorite has been raised and how long it has stayed at this temperature. Under the assumption that the meteorite has been plastically (non-elastically) deformed to an extent still compatible with the retention of its crystal structure, we can calculate the work of compression per cc as being of the order of the ultimate compression strength for nickel-iron, about 2×10^{10} dyne per cm^2 and therefore the heat input is of the order of 2×10^{10} erg per cm^3. Taking a density of 7.8 gm per cc, and a specific heat of 7×10^4, a temperature rise of 300° can be calculated. The total temperature rise may well be doubled, since the shear deformation will also add a heat input, and so will various reflected shocks which traverse the meteorite material. Because of the irregular shapes involved, the shock waves can be reflected many times and the meteorite can therefore be heated even to temperatures approaching the point at which the crystal structure can be destroyed.

It is important to notice that the shock waves heat the meteorite throughout its volume, not just a surface heating. As a result, depending on size, the meteorite will keep its temperature for a time interval of the order of a day and then slowly approach the planetary temperature of about 200 to 300°K.

(It is interesting to note that under this picture stony meteorites will show a different behavior. They are so brittle that plastic deformations are too small, so that no appreciable heating will take place. If the shock wave is strong enough, the material will be pulverized; but the unpulverized material which we recover in the form of meteorites should retain most of its gas content. In this way we can explain the good validity of the argon-potassium ages in stony meteorites.)

The heating of iron meteorites in the collision process which creates them may thus produce important physico-chemical effects. For example, it would tend to accelerate the outward diffusion of any radiogenic He^4 along channels at the boundaries of the crystal grains. According to the cosmic-ray evidence on six meteorites, a collision (or a set of collisons) took place about 300 m y ago. This value is close to the 200 m y figure cited by *Dalton* and others [1953] as a 'solidification' age. Provided we can accept their values of the uranium content of iron meteorites (and these are doubtful), then the simplest explanation of their results is to suggest that the breakup may also be responsible for the escape of radiogenic helium.

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Polymorphism in the Earth's Mantle*

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Abstract—Polymorphism has been proposed to explain seismic discontinuities without chemical change. Topological and thermodynamic classifications of polymorphism indicate a much wider range of possible types than previously described, with the further possibility of seismic discontinuities independent of density changes. Polymorphic transformations are topologically classified as: (1) open packing to *cp* (close-packed), (2) rearrangement of interstitial atoms in *cp* structures, (3) coordination change, (4) electronic transformation, and (5) rearrangement of *cp* atoms. Calculation of repulsion energy for coordination change indicates an increase of cation coordination number with high pressure, but the effect of temperature cannot be generalized.

Transformations of types (1), (3), and (4) are first order, with a volume change, latent heat, and change of elastic constants. Types (2) and (5) are second order in an ideal case, with an abrupt change of elastic constants at a critical point, but with volume and heat changes spread over a wide range.

With increasing depth, a single composition might undergo a series of transformations with consequent effect on the seismic observations: a low-pressure open structure collapses to *cp*; the cations move from tetrahedral to octahedral holes, then into high coordination positions where they are an essential part of the packing; and ions release their electrons to the conducting state (starting with the oxygen ion). While interstitial atoms are still present, they may rearrange in response to temperature or pressure changes. At some undetermined stage *cp* atoms may rearrange, as from cubic *cp* to hexagonal *cp*.

Introduction—A dozen recent papers have suggested that changes, downward in the mantle, of seismic velocities, density, compressibility, or electric conductivity could possibly be explained by a change of crystal structure rather than a change of chemical composition. Inasmuch as these papers were concerned mainly with the physical properties of the mantle as such, it seems appropriate to review the possibilities of pressure polymorphism in terms of the structural chemistry involved. As a step in this direction we discuss the whole range of possibilities for a one-component system. We will attempt to relate to this outline the various specific proposals that have already been made for polymorphism in the mantle, but will not try to evaluate quantitatively which, if any, of the possible transformations actually occur in the mantle. The mantle itself is, of course, a system of many components, and while this complicates the details of phase transformation, the ideas which we review concerning packing and coordination should still be valid in a general fashion for an aggregate of multiple components and phases.

Types of polymorphism—Inasmuch as extreme pressures are characteristic of the Earth's interior, some sort of close packing (hereafter abbreviated *cp*) of atoms should characterize structures in the lower mantle. With this as a primary reference for the classification, the following types of transformation are of interest: (1) open packing to *cp*, (2) rearrangement of interstitial atoms in the *cp* structure by (a) hole-atom exchange, or (b) coordination exchange, (3) coordination change (may or may not involve *cp* atoms), (4) electronic transformations, and (5) rearrangements of the *cp* atoms.

The classification is primarily topological, and refers to equilibrium polymorphic states. A classification [*Buerger*, 1948, p. 105] that distinguishes 'displacive' and 'reconstructive' transformations differs in that it is concerned primarily with rate of transformation. The latter viewpoint would be pertinent in some considerations, such as the relation between the rate of a pressure transformation and the rate of change of pressure during convective overturn. Our classification also does not treat separately transformations of the order-disorder type [see, for example, *Buerger*, 1948, p. 108]; examples of these will be found among several of our types.

Transformations have also been classified according to their thermodynamic 'order' [*Ehrenfest*, 1933; *Epstein*, 1937, p. 128]. A phase change of the *n*th order is one in which the first discontinuity of the derivatives of the free energy appears in the *n*th derivative. Thus, a second-order phase trans-

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formation will have no latent heat or volume discontinuity, but will have discontinuities in the heat capacity and compressibility or elastic constants. Intermediate cases are possible in which, for example, the volume changes vary rapidly near the transformation point, with or without a real discontinuity at the transformation point. Furthermore, the integration inherent in a measurement system may indicate an apparent volume discontinuity, with or without a preceding volume anomaly. These transformations have been called anomalous, diffuse, second kind, or one-and-a-half order, and include a number of practical cases, [*Mayer* and *Streeter*, 1939; *Tisza*, 1951; *Sokolov* 1951]. One of the objects of this paper is to suggest correlations of the topological and thermodynamic types of polymorphism.

Transformations from open toward cp structures—Polymorphic transformation in this direction should be important for those compositions which form near the Earth's surface with structures more open than *cp*. The complexes (relatively tightly bonded parts) responsible for any openness of the structure are most simply considered [*Wells*, 1954, p. 536] from a topological viewpoint as nets of connected points characterized by their types of polygons. The extended complexes of silica tetrahedra, for example, are 3-dimensional, 4-connected (coordinated) nets, counting each silicon atom as a point. Transformations from open structures toward *cp* may be subdivided, in terms of the topological changes inside the complex, into subtypes involving (a) change in connectedness, (b) change in rank (number of sides) and proportions of the large polygons, (c) change in stacking arrangements of component 2-D nets, (d) change in dimensionality (that is, extension of the complex in 0, 1, 2, or 3 dimensions), and (e) the (non-topological) deformation of the polygons. These major structural changes may be accompanied by others in which atoms, considered as equivalent points in the simplified topological net, become distinguished in an ordered arrangement.

In subtype (a), note that the *cp* atoms in a structure are 12-connected with each other, and in the ideal case, have a packing coefficient (percentage of volume occupied by atoms, ten times the 'packing index' of *Fairbairn* [1943]) of 74 pct. As noted by *Wells* [1954, p. 849], typical 'uniform' nets of lower connectedness have correspondingly lower packing coefficients: 8-connected, 68 pct; 6-connected, 52 pct; 4-connected, 34 pct; and 3-connected, 23 pct. In these four cases, the packing coefficient is approximately proportional to the connectedness. The transformation from gray to white tin involves a change from *cn* (coordination number) 4 to (deformed) *cn* 6, with a corresponding contraction of 20 pct. Although this transformation has been referred to [*Ramsey*, 1949, p. 414] as an example of contraction related to an electronic transformation (as discussed in a later section), the major effect is evidently one of coordination change. (Actually, the distances to near neighbors in white tin (4 at 3.02 A and 2 at 3.15 A) greater than those in gray tin (4 at 2.80), so any are electronic contraction has been completely masked by structural effects.)

Changes of subtypes (b) and (e) often are part of the same transformation, and they are discussed in detail elsewhere [*Holser*, 1956]. In summary, many 3-D framework structures (with a particular connectedness) may be considered topologically as stackings of 2-D nets, which are, in turn, composed of regular or nearly regular polygons. As the rank and proportion of the polygons of highest rank is increased, the packing coefficient of the structure is decreased. In silicates, however, 8-gons are deformed from their regular aspect until their small diameters approximately equal those of the 6-gons. As a result of the balance of these two effects, the packing coefficient of oxygen in the 8,4-gon structure of sanidine (or other feldspars) does not differ appreciably from that in the 6-gon structure of cristobalite (or tridymite). Calculations of packing for Wells' theoretically derived 4-connected nets indicate that silicate structures are not likely to have packing coefficients that are greater than that of quartz (52 pct) by virtue of rearrangements of this sort, in which the connectedness and dimensionality of the complex is unchanged.

Constituent 2-D nets of a 3-D net may be connected to each other in various ways ((c), above). *Wells* [1954, p. 551] illustrates nine ways of connecting 4,8-gon 3-connected 2-D nets, to form 4-connected 3-D nets. The composition $BaAl_2Si_2O_8$ occurs in two of these stackings, as celsian (Wells no. $16C_1$) and as paracelsian (Wells 8C); the actual as well as the idealized structures have equal packing coefficients (49 pct). Cristobalite and tridymite represent two simple ways of stacking 6-gon 3-connected 2-D nets. They are related, topologically, to the cubic and hexagonal stackings of *cp* atoms, and a variety of intermediate polymorphic structures is possible, as discussed in a later section of this paper.

A framework structure is a 3-D complex, while for a structure that is *cp*, the packed units themselves may be considered as the complexes, so that,

in this sense, a *cp* structure is 0-D. As the dimensionality of the complex decreases, the packing becomes less determined by the interatomic distances characteristic of the inside of the complex, and more determined by the inter-complex distances. It is instructive to compare the polymorphs of elemental phosphorous with the structural complexes of the silicates. In phosphorous, the intra-complex P-P distance is 2.3 A and the inter-complex distance 4 A, as a result the 0-D (yellow) form has a packing coefficient of 21 pct, which is increased to 32 pct in the 2-D (black) form. In the silicates, on the other hand, the oxygen atoms inside a complex are held apart by the repulsion of tetrahedra, while between complexes they can lie in nearly *cp*, so long as they are bound by other cations. The distances inside and outside the complexes are in opposite relation to those in phosphorous. Consequently, in the silicates, we find some inverse correlation of packing coefficient and dimensionality:

Dimensionality of silicate complex	Packing coefficient in percent, and standard deviation among species
3-D frameworks	48 ± 3
2-D layers	56 ± 4
1-D double chains	57 ± 1
1-D single chains	59 ± 2
0-D rings[a]	54 ± 4
0-D *cp*	62 ± 4

[a] Including the rare silicates sharing only one corner between tetrahedral pairs.

Ramsey [1949, p. 414] associates "a 50 pct contraction" (the x-ray data indicates 33 pct) with the electronic transformation (see later section) from yellow to black phosphorous, but evidently, most of this contraction results from the structural rearrangement, the inter-atomic distances being equal so far as one can tell from the rough data presently available. In arsenic the transformation to a metallic state is accompanied by a change from a 0- to 3-D complex and at the same time the *cn* changes from 4 to 6 (distorted); both contribute to the volume contraction of possibly 60 pct.

The high-pressure form of silica, coesite [*Coes*, 1953; *McDonald*, 1956], has a density of 3.01 and a packing coefficient of 55 pct. The structure has not yet been determined, but we have noted above the topological restriction on the formation of a 4-connected framework structure with such high packing. The packing cannot be increased by lower dimensionality, as it is in the silicates, because the lack of other binding cations permits even larger inter-complex distances, resulting in a packing of only 38 pct in silica with the 2-D 4,2-connected complex of the SiS_2 type [*Weiss* and *Weiss*, 1954]. The only possibility for high packing like that of coesite is an increase in connectedness, such as a change of silicon from 4- to 6-coordination with oxygen. On the other hand, the oxygen ions are probably not *cp*, as the packing does not approach that of *cp* structures of oxides such as TiO_2 [suggested by *Birch*, 1952, p. 275], GeO_2, Al_2O_3, or spinel, that are 6-connected. Therefore, a *cp* form of SiO_2 with density greater than coesite seems possible.

The possibility of a transformation, from low-quartz to the slightly more open structure of high-quartz, owing to a high temperature near the base of the crust, has been discussed in detail by *Yoder* [1950] and *Gutenberg* [1951, p. 431–433].

Birch [1952, pp. 272, 274] notes that the densities and compressibilities measured at the surface on specimens of jadeite ($NaAlSi_2O_6$) (which has 1-D complexes) are more like those calculated for mantle material than are those of forsterite (Mg_2SiO_4) (which has 0-D complexes). He, therefore, suggests transformation of magnesium silicates to pyroxene or further to an 'oxide structure' such as that of corundum (Al_2O_3), for which the required high density and low compressibility has been measured. *Verhoogen* [1953, p. 338] points out that chrysoberyl (Al_2BeO_4), with the forsterite structure, also has a high density. The SiO_3 single chains in the pyroxene structure fit together in such a way that the oxygen atoms are nearly in a *cp* arrangement, being separated slightly by the large cations. In other words, no oxygen ions are sufficiently 'inside' the complex to be separated by repulsion between silica tetrahedra. The unit cell sizes for various compositions are directly proportional to the ionic radii of the *cn* 6 cations, and the very small volume of the jadeite composition is fully accounted for by the small Al^{3+} ion. Returning to *Birch*'s [1952, p. 264] data note that among the few available measurements various compositions with the chain pyroxene structure and the *cp* forsterite structure actually have densities and compressibilities within the same range. Part of the confusion arises from an implied correlation of a structural arrangement with a few measurements of a physical property on specific compositions. Thus, it may not be 'oxide structures,' but oxide compositions that gave the tabulated properties sought by Birch. In the following discussion, a designation of structural type does not imply that

the composition in question will have the properties tabulated for the type example.

Whatever the composition, it seems likely that any open structures are likely to transform in the mantle to some sort of *cp* arrangement, although more than one phase may result. Experimental work in this laboratory by G. C. Kennedy and others (unpublished) has confirmed collapse of many open structures, including most feldspars and feldspathoids. The transformation toward *cp* will be first-order, although any order-disorder transformations, or stacking rearrangements (subtype (c)), may be of second-order. We now consider the possible transformations among *cp* structures.

Rearrangement of interstitial atoms in the cp structure: (*a*) *Hole-atom exchange*—If a *cp* arrangement involves essentially anions, then there are two holes of *cn* 4, and one hole of *cn* 6, for each *cp* atom. MX_2 compositions with *cn* 6 will, therefore, fill only half the possible *cn* 6 holes, and conceivably could do so in a large number of ways. An example is provided by the following series of structures, all based on an approximately constant *cp* packing of the hexagonal type (*hcp*): (1) Rutile (TiO_2) type: TiO_6 octahedra share two edges to form chains diagonal to *cp* layers, linked at corners. (2) Diaspore ($HAlO_2$) type: chains parallel to *cp* layers, linked at other edges and at corners. (3) Brucite ($Mg(OH)_2$) type: octahedra share two edges to form hexagonal sheets, not linked together. (The relations among these types are exemplified by MnO_2, which occurs with each of the three structures, as pyrolusite, ramsdellite, and δ-MnO_2, respectively. The structure of another form, γ-MnO_2, is probably some kind of mixture of the rutile and diaspore types. Pyrolysite is formed irreversibly when any of the other forms are heated and may be the only truly stable structure for MnO_2. Lattice constants indicate five per cent contraction in the ramsdellite → pyrolusite transformation, but the wide variability of chemical analyses of MnO_2 [*Wells*, 1950, p. 371] casts some doubt on its significance. The transformations are not accompanied by "any large energy effect" [*McMurdie* and *Golovato*, 1948, p. 598].)

The *cp* anionic framework that remains during this kind of transformation tends to restrict it to second order, with no latent heat or volume change; actual discontinuities should be small.

In *cp* structures of formula types such as MX_2, M_2X_4, and MX (*cn* 4 only), similar polymorphic transformations are conceivable. Furthermore, the arrangement of filled and unfilled holes may become disordered at high temperature. (Such is apparently the case in chalcocite (Cu_2S) and maghemite (Fe_2O_3). Where two kinds of interstitial atoms are present, as Cu and Fe in chalcopyrite ($CuFeS_2$), these also may disorder.)

Rearrangement of interstitial atoms in the cp structure: (*b*) *Coordination exchange*—*Cp* structures in which both *cn* 4 and *cn* 6 positions are occupied may exchange atoms between these two types of position. As an example consider the spinel (Al_2MgO_4) structure, which has oxygen in *ccp* positions with half of the *cn* 6 (B) holes and an eighth of the *cn* 4 (A) holes occupied by cations. Most compounds with this structure contain two or more species of cations, in which case the distribution of cations is governed by the following factors [*Verwey* and *Heilmann*, 1947]: (1) Maximal charge neutralization: cations of high charge in high coordination (*cn* 6) and cations of low charge in low coordination (*cn* 4), enabling a more localized neutralization of charge. (2) Size: large cations in large (*cn* 4) holes. (3) Directivity of bonds: covalent bonding with a 109° bond angle, as found, for example, in the hybrid sp^3 bond types of Zn^{2+} and Fe^{3+} atoms, favoring *cn* 4 [see also *Goodenough* and *Loeb*, 1955].

Crystal energy calculations show that, in most spinels, the charge (1) is more important than the size (2), giving the two types, $B_2^{2+}A^{3+}O_4$ (normal 2–3 spinel), and $B^{4+}B^{3+}A^{3+}O_4$ (inverse 2–4 spinel) [*Verwey* and *Heilmann*, 1947, p. 180]. Reversals of these arrangements, $B^{3+}B^{3+}A^{3+}O_4$ (inverse 2–3 spinel), and $B_2^{2+}A^{4+}O_4$ (normal 2–4 spinel) are explained by a dominance of the third factor: tetrahedral bonding of certain atoms. Where two kinds of atoms are present in B positions, crystal energy calculations also indicate a large difference in favor of a tetragonal (pseudo-cubic) structure with the two kinds of atoms ordered among the *cn* 6 positions [*deBoer*, *van Santen*, and *Verwey*, 1950, p. 1033].

These structures are ideals attained only at low-temperature equilibrium. As the temperature is increased, three sub-types of transformation may take place. In the first of these, atoms are exchanged between *cn* 4 and *cn* 6 positions. As discussed elsewhere [*Holser*, 1955], this expresses a tendency to change gradually from the inverse to the normal structure, or vice-versa. Thus, a crystal with the gross composition Fe_2CuO_4 has the inverse structure, $(FeCu)\,FeO_4$, at low temperature, but at 900°C has transformed more than 30 pct of its structure to the normal type, $(Fe_{1.3}\,Cu_{0.7})\,(Fe_{0.7}\,Cu_{0.3})O_4$. In this intermediate state, an or-

dering of the normal and inverse units of the structure is theoretically probable, but has not been observed. No spinels have yet been taken to a high enough temperature to effect a complete transformation. The theory [*Holser*, 1955] predicts a gradual but accelerating continuation of the transformation, with no discontinuity in the distribution function for the two structures, but a probable critical point for complete transformation. Therefore, although comparison of lattice constants indicates about a one per cent contraction for the normal-inverse transformation due to the better fit of cations in the latter case [*Verwey* and *Heilmann*, 1947, p. 180], the change in volume would probably occur as 'anomalous' thermal expansion over a range of temperature, and the transformation would be second order. Increasing pressure should reverse the effect of increasing temperature in this transformation, as in many others.

Until a decision is made as to which of several factors cause the observed *cn* 6 $\rightleftharpoons$ *cn* 4 transformations [*Holser*, 1955], it is not possible to predict which compositions and structures will be susceptible to them. Thus, the transformation of forsterite to an 'inversed forsterite' structure, $(MgSi)MgO_4$ is a possibility that must be considered in the Earth's mantle. This also involves a change in *cn* for Si, as discussed in more detail below.

The second sub-type of transformation in the spinel structure does not involve a *cn* exchange. As noted above, two kinds of *cn* 6 atoms are ordered at low temperatures, and these may become disordered with rising temperature. The deviation of the tetragonal structure from cubic dimensions decreases at an increasing rate, until at a critical temperature [*Bertaut*, 1951] the structure is cubic with the *cn* 6 atoms completely disordered.

The third possibility is a transformation to complete disorder among all *cn* 4 and *cn* 6 atoms, which would again involve an exchange of coordination. It is not yet possible to decide whether the first or third sub-types are dominant in the spinels, but at sufficiently high temperatures a complete disordering should obtain among all the interstitial atoms. Other examples of order-disorder transformations have been described in previous sections. These transformations should be of the second-order thermodynamic type with no density discontinuity. Measurements on alloys [*Wilson*, 1939] indicate that high pressure slightly decreases disorder, in opposition to rising temperature. Without further theoretical or experimental work, it would be difficult to guess whether mantle pressure would be sufficient to overcome the disorder induced in a given structure by mantle temperature.

Rearrangement by coordination change—An unbalanced change in cation *cn* represents another possible type of polymorphism with constant *cp* anion structure. This polymorphism is exemplified in the halides of univalent elements, which occur variously in the structures of sphalerite, halite, and CsCl, with *cn* 4, 6, and 8, respectively. (In CsCl, the cations are beginning to take a decisive part in the *cp*.) The relative stability of these structures is evaluated from lattice energy calculations by *Huggins* and *Mayer* [1933]. The repulsion energy should dominate at high pressures, and therefore the relative stability of the structures will be governed by (1) the cation coordinations, of 4, 6, or 8, and (2) oppositely by the cation-anion separations which in the limiting case of no volume change are in the ratio 0.87:1.00:1.09, for the sphalerite-, halite-, and CsCl-type structures respectively. Calculations for some halides [*Jacobs*, 1938, pp. 472–474] show that at least for these compounds the radius change is the more important, and the higher coordination is more stable at high pressure. (Similar calculations by *Mayer* [1933, p. 333] and *Huggins* [1951, pp. 250–251] do not correct for the change in r separately in each term of the energy equation and consequently the conclusion, which *Seitz* [1940, p. 90] bases on Mayer's calculations, that the repulsion term favors a low *cn*, is incorrect.) Preliminary calculations by one of us (W. T. H.) for coordinate groups of oxygen ions about Si^{4+}, Mg^{2+}, and Na^{+}, reinforces the conclusion that uncompensated changes of cation *cn* under increasing pressure should be from a lower to higher *cn*.

Birch's [1952, p. 274] suggested high pressure forms of SiO_2 with rutile structure and of $MgSiO_3$ with corundum structure are plausible examples of close-packings with cation *cn* 6. (*Verhoogen* [1953, p. 338] thinks these structures unlikely because of the *cn* 6 required for silicon, but this is already known in the halite-like structure of SiP_2O_7, and also in glass.) The range of these transformations is not restricted by the formula type. For example, a spinel (M_3O_4) with some *cn* 4 cations might transform to a halite structure with random interstitial vacancies (like that of iron-poor wustite (FeO)).

Increasing *cn* beyond 6 necessitates a structure in which cations enter into the *cp* with the anions; finally no cations remain as interstitial (as in CsCl and fluorite).

In the garnet and glaserite structural types,

some but not all of the cations are involved in the *cp*. Ca_2SiO_4 has the olivine structure at low temperature, and the denser glaserite structure with *cn* 10 at high temperatures [*Bredig*, 1950, p. 189]. The possibility of a high pressure phase of the garnet type independently supports an 'eclogite' hypothesis [*Bowen*, 1928, p. 305; *Birch*, 1952, pp. 271–272], without necessitating any special composition.

The effect of temperature on these transformations is more difficult to estimate. For complex oxides *Bredig* [1945, pp. 542–549] postulates a general increase in coordination number with increasing temperature (at low pressure). This would give no reversals of *cn* transformations with depth in the mantle. *Buerger* [1948, pp. 107, 115; 1951, pp. 203–205; see also *Huggins*, 1951, pp. 248–250] on the other hand argues for a decrease in *cn* with increasing temperature. Actually both occur, and according to *Birch* [1942, p. 176; see also *Bridgman*, 1945, p. 93], "There is, however, no way of knowing whether the high-temperature phase will be the high pressure phase or the low pressure phase.... The equilibrium between two solid phases is frequently with $\Delta T/\Delta P$ negative." The transformations with temperature are controlled by the entropy, which may be computed from the fundamental frequencies of vibration in the crystal [*Seitz*, 1940, p. 481]. But the relations of the frequencies to fundamental structural parameters are considerably more complex than are those of the crystal energy as is evident from an inspection of *May's* [1937, pp. 343–347] calculations of the temperature of transformation in alkali halides. Even the simplification used for the pressure transformations, that the principal forces are repulsive at extreme pressures, will not permit any generalizations. Inhibition of a *cn*-type pressure transformation, or actual reversal of such a transformation, is possible as a result of the corresponding rise in earth temperature. Transformations with *cn* change generally will be first-order.

Electronic transformations—Transformations of the electronic state of the atoms themselves may be induced by extreme pressures or temperatures. If the pressure is sufficiently high electrons are effectively freed from the nuclei. The resulting phase is metallic, with a high density that is a function only of the pressure and atomic number, as calculated on the Thomas-Fermi-Dirac model [*Elsasser*, 1951]. *Ramsey* [1949, p. 410; 1950; 1954] points out that transformation to a metallic phase may be discontinuous, and postulates that the discontinuity at the boundary of the Earth's core is a transition of olivine to such a metallic state. While transformations to a metallic state have been observed in such elements as arsenic, phosphorous, tin and tellurium, their energy and volume changes should not be used to imply [*Ramsey*, 1949, p. 414] similar changes during possible electronic transformations in minerals, because these transformations all include topological changes that undoubtedly overshadow any volume effects of the change in electronic structure, as discussed in detail in a previous section.

Information on the energy required for electronic transformations in the silicates is conflicting. *Ramsey* [1949, p. 421] has suggested an activation energy, for the transformations of silicates to the metallic state, of about 10 ev, based on the ultraviolet absorbtion spectrum of quartz. Ramsey's tentative assumption that the transformation is due to excitation of the molecule SiO_2 seems unwarranted. The particular electronic changes to be expected in olivine during a transformation depend on the relative energy levels in the olivine structure, and on the change in these relative levels with pressure. The complexity of the olivine structure makes computations difficult even for low pressure, but the electronic states in Mg_2SiO_4 with a hypothetical normal spinel structure may have similar relations. An energy level diagram was constructed after the method of *Seitz* [1940, pp. 447–449], using the local Madelung constants for the spinel-type structure published by *Verwey, de Boer*, and *van Santen* [1948, p. 1091]. The easiest electronic transition turns out to be the removal of an electron from the oxygen ion into a conduction band ($2p^6 3s$ state) of the magnesium atom, with an activation energy of about 20 ev. If the structure were inverse ($Mg(MgSi)O_4$), the silicon, now in *cn* 6, would also become conducting at about the same energy level. *Runcorn* and *Tozer* [1955, p. 101] mention ultra-violet absorbtion measurements on olivine which indicate an activation energy of only 3 ev, and derive a similar answer from measurements of the conductivity of olivine. However, *Hughes* [1955] interprets these same conductivity measurements as indicating ionic rather than electronic conduction. There is also the possibility that the absorbtion measured for olivine was due to impurity or imperfection centers in the crystal, rather than to a principal electronic excitation. All of these estimates refer to relatively low pressures, and the activation energy will decrease as the conduction band is broadened at low volume. Apparently present data are insufficient to estimate the activation energy and corresponding

pressure of a possible electronic transformation in Mg_2SiO_4 or other silicates.

Knopoff and *Uffen* [1954, p. 481; see also *Ramsey*, 1949, p. 420] have shown that temperatures higher than those likely in the mantle would affect the Thomas-Fermi model by less than eight per cent.

Rearrangements of cp *atoms*—The possibility of stacking *cp* layers in either a cubic or a hexagonal environment gives rise to a multiple polymorphism interpreted [*Schneer*, 1955] as a statistical increase in the proportion of layers in the high-energy environment with increase of temperature. Finally, at a critical temperature analogous to a disordering temperature, the process would be complete. Volume differences (if any) between the cubic and the all-hexagonal (2H) state would be spread over the whole temperature range from 0° *K* to the critical temperature, so that there would be no discontinuity in the $V - T$ curve at the critical point, but rather a change in slope. Below the critical temperature the *ccp* and *hcp* layers tend to assume some ordered sequence, but there is also the possibility [*Jagodzinski*, 1949] that the temperature may induce a disordered array.

As the 'interstitial' atoms become relatively large (but still not large enough to change the topological arrangement) these ideal relations may no longer obtain, especially where the interstices are filled with fewer number or larger variety of ionic species. Thus in TiO_2 the O^{2-} ions are in highly distorted *cp* arrangements, with only half the *cn* 6 holes filled by large Ti^{4+} ions. The polymorphs have the following relations:

Structure	Rutile	Brookite	Anatase
Oxygen packing[a]	121212... (*hcp*)	1232123... (mixed)	123123... (*ccp*)
Formula volume (A^3)	29.2	32.0	33.8

[a] Stacking positions of the (distorted) $O^{=}$ layers; see, for example, *Wells* [1950, pp. 85–87].

The transformations are first order; anatase → rutile, with a 14 pct reduction in volume (at surface temperature and pressure) and has been performed irreversibly at 1000 bars and 850°C [*Thienchi*, 1946]. This example only demonstrates the possibility of a volume change while retaining *cp* of anions, and does not imply correlation of large volume with *ccp*. The changes are specific to the particular structures and composition involved. Furthermore, when the anion layers have been rearranged, it becomes difficult to define whether or not the cation arrangement has also 'changed' as described earlier under *Rearrangement of interstitial atoms in the cp structure: (a) hole-atom exchange*.

A similar transformation has been proposed for Mg_2SiO_4, from the (*hcp*) olivine- to (*ccp*) spinel-type [*Bernal*, 1936; *Mason* 1953]. Mg_2GeO_4 has been transformed in this way, when cooled through 1005°C at surface pressure, with an 8.2 pct volume contraction (measured at surface temperature [*Roy* and *Roy*, 1953]). However, it is not known whether the spinel-type structure was normal or inverse, or for that matter whether the forsterite-type was 'inverse'; the considerations of an earlier paragraph suggest that the spinel form may be inverse. The ideal limiting case for this type of transformation would have no volume discontinuity, so no inference should be drawn concerning an Mg_2SiO_4 transformation, until the specific structures determined and the reason for non-ideality in Mg_2GeO_4 is evaluated.

Discussion—This survey shows a very wide variety of conceivable polymorphic transformations, and the situation may be more complex in multi-component systems. Our choice of postulated structures for polymorphism in the mantle should not be restricted arbitrarily to any particular group of these transformations. Furthermore, we should not correlate physical properties too strictly with structural type. However, we might make the following generalizations.

Transformations from an open toward a *cp* structure (type 1) are generally first order, with a change in volume and heat content, as well as in elastic constants. Electronic transformations (type 4) are also first order, transformations involving coordination change (type 3) are expected to be first order, but the volume change should be relatively small. Those transformations which involve a rearrangement of interstitial atoms (type 2) or of the *cp* atoms (type 5) should be of second or higher order in the ideal case, having a possible change in elastic constants, and consequently seismic velocity, but no discontinuity in volume. They are possible only in situations where an equilibrium structural mixture of the two end-states is physically realizable. Departures from ideality should be small, but some cases that are formally ideal may show accelerated changes in volume near the critical point of the transformation, which might look like a discontinuity if the measurements did not have sufficient discrimination. Physically these anomalous second-order transformations result from a cooperational effect in which the in-

crease in proportion of the high-temperature form decreases the energy difference involved in its formation [*Schneer*, 1955, p. 280]. Such cooperational effects are likely in the second-order polymorphic transformations considered above.

Those transformations that are second order (or nearly so) are controlled principally by temperature. If the data on disorder in alloys [*Wilson*, 1939] may be generalized, the effect of high pressure is small but opposite to that of temperature. On the other hand, the electronic transformations are controlled principally by pressure, with little temperature effect. Transformations of type (1) also will be sensitive to pressure. The importance of pressure in increasing coordination number (type 4) has been demonstrated, but no generalization can be made concerning the effect of temperature on this type of transformation.

Verhoogen [1953, p. 338] has objected to *Birch*'s [1952, p. 274] postulated polymorphic changes because they would give sharp changes in properties whereas the changes observed in the mantle are gradual. In addition to the possibility of solid solution, which Verhoogen states to be inadequate, we now have two other possible sources of 'gradual' changes in seismic velocities. Firstly, the wide variety of possible polymorphic transformations with a given composition might explain such changes as the result of a number of small changes associated with first-order (or second-order) transformations. The spectrum of transformations could include any or all types that we have discussed above. Secondly, second-order transformations will probably be preceded by an anomalous gradual change in properties. The practical question as to whether such gradation in properties would be spread out over a range of mantle temperatures and pressures sufficient to be discerned by seismic observations, is one that cannot be answered with any generality.

Conversely, the wide variety of possible polymorphic transformations lessens the necessity of a correlation between variations in seismic velocities and changes of composition. We cannot correlate velocities with composition, with the confidence previously assumed, at least unless many of the above possibilities are eliminated by quantitative calculation.

The evaluation of the temperatures and pressures (and compositions) for which the polymorphic transformations will occur (if they do) is beyond the scope of this paper, which attempts only to outline a framework that may be useful in any future calculations or speculation on this subject.

Acknowledgments—This research was begun in 1953, when the authors were at Cornell University, under the auspices of the Department of Geology. We wish to acknowledge helpful discussions with J. A. Krumhansl, Jean Verhoogen, Leon Knopoff, and Rustum Roy.

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Deflections of the Vertical in New Britain

WILLIAM M. KAULA

Nineteen astronomic observations made in connection with a control survey by Australian and U. S. Army topographic forces of the island of New Britain (Territory of Papua and New Guinea) indicate unusually large deflections of the vertical throughout the 450 km length of the island.

After adjusting the datum to minimize the deflections, the rms of ξ is $\pm$ 24″ and of η is $\pm$ 21″, or 32″ for the total deflection. The pattern of the deflections shows a marked correlation with the topography of the island.

The geodetic control was provided by a complete ring of shore-ship triangulation around the island 1360 km long. The misclosure of this ring was 45 m; hence, the uncertainty of any geodetic latitude or longitude should not be greater than $\pm$1.5″.

Matupi astronomic station, origin of the system, was observed with a Bamberg transit in accordance with USC&GS first order specifications. All other astronomic positions were observed with Wild T-2 theodolites, for the purpose of getting latitude and longitude to compute azimuth from prime vertical stars. Latitude was observed by the method of circum-meridian altitudes using two pairs of stars; hence, latitude uncertainty should be less than $\pm$3″. Longitude was observed by meridian transits, using two pairs of stars and stop watch comparison with chronometer checked by WWVH time signals; hence, longitude uncertainty should be less than $\pm$3″, and systematic error less than $\pm$2″.

The combined uncertainty of the deflections should thus be not greater than $\pm$4″ for ξ and $\pm$5″ for η.

In the table, ξ is + for astronomic latitude north of geodetic, and η is + for astronomic longitude east of geodetic.

Station	Geodetic position, Matupi Datum						Deflections			
	South latitude			East longitude			Matupi datum		Adjusted datum	
	°	′	″	°	′	″	ξ″	η″	ξ″	η″
Matupi	04	14	12	152	11	27	0	0	+15	+19
Put Put	04	33	38	152	21	52	−2	+19	+13	+38
Wide	05	04	51	151	57	23	−8	+21	+7	+40
Wagin	05	27	37	152	02	18	−47	+22	−32	+41
Cunningham	05	38	39	151	30	38	−36	+18	−21	+37
Melelo	06	01	01	151	00	31	−54	+3	−39	+22
Amgen	06	11	43	150	32	07	−53	−11	−38	+8
Andro	06	16	43	149	47	37	−46	−37	−31	−18
Masas	06	05	29	149	11	20	−49	−34	−34	−15
Bach	05	47	37	148	30	06	−28	−41	−13	−22
Rottock	05	31	28	148	50	04	+4	−28	+19	−9
Molo	05	30	03	149	34	27	+1	−36	+16	−17
Riebeck	05	28	11	149	56	41	+2	−22	+17	−3
Worri	05	15	51	149	59	48	+6	−23	+21	−4
Wangore	05	07	51	150	04	51	−2	−24	+13	−5
Stettin	05	33	04	150	09	52	+7	−23	+22	−4
Commodore	05	31	03	150	43	41	+2	−25	+17	−6
Gula Gula	05	06	37	151	08	40	+9	−30	+24	−11
Hixon	04	56	03	151	30	50	+11	−10	+26	+9

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Editor's comment—The above note was transmitted by W. A. Heiskanen as "a good example of valuable scientific results one can obtain in connection with routine measurements."

Discussion of "A New Determination of the Figure of the Earth from Arcs"

[*Trans.* AGU, **37**, 534–545, 1956]

BERNARD CHOVITZ AND IRENE FISCHER

W. A. Heiskanen (Institute of Geodesy, Photogrammetry and Cartography, Ohio State University, Columbus, Ohio). This paper is one of the most important papers in the geodetic literature of the last decades. Through the efforts of the Geodetic Section of the Army Map Service (AMS), under the leadership of Floyd W. Hough, the gap in the arc Cairo-Capetown was filled, so that the arc of 10,900 km from northern Finland to Capetown became available. Since also the Pacific arc of 11,000 km from Alaska to the 41° S latitude and the 5300-km long arc along the 52° parallel from Belgium to 82° E longitude and several other arcs were used, the dimensions obtained from this vast astro-geodetic material are as good as they can be, when the gravimetric evidence is neglected.

The publication reveals also the enormous amount of work necessary to get the results: long triangulations in difficult conditions, costly in time and money; astronomic observations; adjustment computations of the triangulations; and computation of hundreds of deflections of the vertical, topographic-isostatic reduction of them; and finally computation of 36 different solutions for the parameters a and α of the reference ellipsoid. We have reason to congratulate the AMS for this achievement.

As the authors have emphasized that the publication is of tentative character only, I would like to make some comments in the hope that at least some of them will be considered when the final Earth dimensions are to be computed. Since in the publication no data have been given concerning the closure errors of the triangles, accuracy of the astronomic observations, and deflections of the vertical at the astro-geodetic points of different arcs, only some general statements and comments are made.

(1) It may be that the strange fact that the Pacific arc gives larger value for the equatorial radius a than do the arcs of the Old World, is caused partly by the difficult observation conditions, partly by the serious systematical errors brought about by the lateral refraction and by the deflection of the vertical at the mountainous triangulation points, both of which can even exceed one second of arc for one single direction, and partly by the inaccuracy of the topographic-isostatic reduction of ξ and η, since the topographic maps in undeveloped areas are hardly sufficiently accurate. The arcs along the mountain chains have, in general, not the same 'face value' as the arcs over smooth topography. What is the average closure of a triangle in different chains? Is it of the order of 1.″0 to 1.″5 as in southern Europe and northern Africa or is it larger or smaller? Is the relative accuracy of the triangulation better than 1:50,000 if the observation conditions are unfavorable? This relative accuracy would explain the differences of 100 to 150 m between the different a values.

(2) The paper shows that the ξ and η values, without the topographic-isostatic reduction, have in mountainous regions only little significance in determining the equatorial radius a.

(3) When the deflections of the vertical jump as much as 20″ to 35″ between two consecutive astro-geodetic points, as at the approximate latitudes −15° and +15° in the 98° meridian in America and at latitude +35° in the 24° meridian in Europe, they can hardly be used in computation of the geoid undulations N. In such cases the distance between the astro-geodetic points used should hardly exceed ten km.

(4) It is regretted that the gravimetric evidence has been neglected. It has been repeatedly emphasized (for instance, the writer since 1950 has done so in at least a dozen publications) that it is already possible to compute gravimetric values ξ_g, η_g, and N_g at the initial points of some different geodetic datums and at many astro-geodetic points or in their vicinity with rather high accuracy.

If the deflection of the vertical used at the initial point is, say, 4″ wrong, it causes a fictitious N-value which increases with the distance along the arc nearly linearly, 20 m/1,000 km. If, for instance, the difference of the absolute deflection ξ_g at the astro-geodetic points used in Finland, latitude 65°, and in Egypt, latitude 30°, is 4.″1, as we have obtained in Columbus gravimetrically, it means that the astronomically observed central

angle Finland-Egypt needs a correction of 4."1, and the equatorial radius a obtained from this arc, while using the astronomic central angle, needs a correction of 200 m.

(5) If the ξ_φ, η_φ, and N_φ had been computed for some astro-geodetic points, the most effective condition equations of the form

$$\sum_1^n (\xi_\varphi - \xi_a)^2 = \text{minimum} \qquad (1a)$$

for the meridian arcs

$$\sum_1^m (\eta_\varphi - \eta_a)^2 = \text{minimum} \qquad (1b)$$

for the east-west arcs, and

$$\sum_1^\ell (N_\varphi - N_a)^2 = \text{minimum} \qquad (2)$$

for the N-control, would have been available (n and m are the numbers of the astro-geodetic points used for the meridian and east-west arcs, and ℓ the number of the N-values). Only relatively few astro-geodetic points, say, four to six but not less than two, would have been necessary for an arc, if only (1a) and (1b) had been used. Since ξ_φ, η_φ, and N_φ are, as we know, independent of the a value and of ξ_0 and η_0 at the initial points, while the ξ_a, η_a, and N_a depend on them, the condition equations would give best correction to the equatorial radius a.

Although the value $a = 6378260$ m, obtained by Chovitz and Fischer, because of the super-long arcs used, hardly needs correction larger than 50 to 100 m, it is methodically a weakness not to consider the gravimetric control, which would decrease the standard error of the obtained a value essentially and at the same time give the actual geoid not only at the astro-geodetic points but in many other places as well.

Of course, it is not too difficult to use the gravimetric control later on. If desirable, the Columbus group is glad to cooperate and compute the ξ_φ, η_φ, and N_φ values at the needed points.

Bernard Chovitz and *Irene Fischer* (Army Map Service, Washington 25, D. C., Author's closure)—Heiskanen's kind words on the work of the Army Service are very much appreciated. We wish to make the following remarks on his comments.

(1) The values of the major axis a given in the first paragraph of Table 2 are not directly comparable because they are combined with different values of the flattening. The second paragraph lists values based on the same fixed flattening of 1/297 and there it can be seen that the Pacific arc gives smaller and not larger values of a than the Old World.

It is agreed that arcs along mountain chains are less desirable than arcs over smooth topography. However, according to the Inter-American Geodetic Survey, the average closure of triangles along the west coast of South America is 0."95, the length checks average 1:105,000, and the probable error of an observed direction is $\pm$0."43.

(2) The improvement through isostatic reduction in South America was pointed out in the discussion on isostasy.

(3) The two extreme jumps in deflections at consecutive points on the South American arc are brought down by isostatic reduction as seen when comparing Figures 2 and 4. This is a point in favor of the isostatic theory. The jump in Crete does not disappear by this reduction; it seems to indicate a real geoidal slope. As a ten-km interval between astro-geodetic points across the Mediterranean via Crete is not possible, dense gravimetric coverage of this tie would be desirable.

(4) The purpose of this preliminary study was limited to investigating the contribution of the new astro-geodetic evidence only. Eventually, gravimetric and astro-geodetic data should yield the same answer. There is some point in using them separately for what they are worth.

(5) This method is a type of study different from the one planned by the authors as explained above. The offer of cooperation by the Columbus group for the final AMS study of the figure of the Earth is greatly appreciated.

Discussion of "On Estimating Streamflow into Tidal Estuary"

BY DAVID K. TODD AND LEUNG-KU LAU

[*Trans.*, **37**, 468–473, 1956]]

D. W. Pritchard (Chesapeake Bay Institute, The Johns Hopkins University, Baltimore, Md.)—The estuary offers many interesting and important problems to the physical hydrographer, and it is encouraging to find that hydrologists are extending their work into this intermediate zone between the river and the ocean. It is unfortunate, however, that this paper by Todd and Lau exhibits a lack of understanding of the mechanisms of circulation and mixing in a tidal estuary.

To a casual reader the concepts presented by these authors are disarmingly clear and simple. Unfortunately, they have not used the basic hydrodynamic concept of continuity in its complete form which has led them to misinterpret the equations they develop, particularly their Equ. (1). The error results from the assumption that sea water on the one hand and fresh water on the other can be considered as *the* two species involved in the mixing processes in an estuary when, in fact, the two separate species which are involved are the salt and the water. The processes of turbulent diffusion, or 'mixing,' can lead to a net upstream transport of salt without a net upstream transport of water. This point will be discussed further below. Let us now consider some specific aspects of the paper.

The authors have stated certain limitations on their development. A fundamental requirement is that the estuary be sectionally homogeneous, that is, it shall have no vertical or lateral salinity gradients. This is an unfortunate restriction to place on estuarine studies, since the majority of estuaries do exhibit some degree of vertical or lateral stratification, with accompanying circulation patterns related to the mass distribution. The characteristic circulation patterns in the various types of coastal plain estuaries have been discussed by *Stommel* [1953] and by *Pritchard* [1952, 1955]. However, an adequate study of even this most simple of estuarine types would be welcome, so that one should not be unduly critical of this aspect.

Todd and Lau develop (1) on the assumption that sea water and fresh water can be considered as the two species in a mixing process. Their equation is

$$Q_f = FAV \qquad (1)$$

where Q_f is defined as the instantaneous fresh water volume flow through a cross-section of area A, having an instantaneous sectional velocity V, and a fresh water fraction F. The basis of their proposed method for calculation of streamflow into the estuary is the determination of F, A, and V over one or more tidal cycles, and the integration of (1) over this time period. They assume that the river flow per tidal cycle is

$$\int_0^T Q_f \, dt = \int_0^T FAV \, dt = R \qquad (3)$$

where T is a tidal period, and R is used here to designate the volume rate of river flow per tidal cycle. Todd and Lau carried out this integration numerically, and did not formally express their procedure in the manner presented here.

Much could be said concerning the authors' assumption that the velocities obtained from U.S.C. & G.S. can be used for the instantaneous velocity V. However, since it will be shown that the basic concept expressed by (1) is not valid, suffice it to say that such a substitution can be seriously questioned.

For purposes of evaluating the reality of (1), consider an estuary with a single source of fresh water, the river, entering the upper end. The coordinate system has the origin in fresh water at the head of the estuary. The x_1 coordinate is directed down the estuary along the central axis, the x_2 coordinate is directed horizontally from the center of the estuary toward the right hand side, and the x_3 coordinate points vertically downward.

If v_i is the instaneous velocity, and v_1, v_2, and v_3 are the rectilinear components of this velocity along the coordinates x_1, x_2, and x_3, the equation of continuity for an incompressible fluid can be expressed as

$$\partial v_i / \partial x_i = 0 \qquad (4)$$

Let $A = A(x_1, t)$ be the cross-sectional area of the estuary at x_1. Then integrating (4) over the area A we have

$$\frac{\partial}{\partial x_1} \iint_A v_1 \, d\sigma + \iint_A \frac{\partial v_2}{\partial x_2} \, d\sigma + \iint_A \frac{\partial v_3}{\partial x_3} \, d\sigma = 0 \qquad (5)$$

Since there can be no flux of mass through the boundaries (surface, sides, and bottom) of the estuary, the last two integrals vanish, and we have

$$\frac{\partial}{\partial x_1} \iint_A v_1 \, d\sigma = 0 \tag{6}$$

Now, if we assume vertical and lateral homogeneity, such that $v_1 = f(x_1, t)$ only, we have

$$\frac{\partial}{\partial x_1} (Av_1) = 0 \tag{7}$$

We would have the same result if v_1 were considered to represent the mean sectional velocity, without requiring the restriction of sectional homogeneity.

Both A and v_1 are functions of longitudinal distance x_1 and time t. However, their time variations being harmonic and of tidal period, the integral of the product (Av_1) is no longer a function of time, providing the river flow and tidal range is considered constant. Hence from (7) we have

$$Av_1 = f(t) \tag{8}$$

only and

$$\int_0^T (Av_1) \, dt = \text{constant} = R \tag{9}$$

Since we can locate the cross section anywhere in the estuary, even up into the river itself, the value of this constant is simply the volume rate of river inflow per tidal cycle, which we have designated as R.

The v_1 in our notation is identical to the V in the notation of Todd and Lau. A comparison of (9) with (1) shows that the assumptions made by Todd and Lau that $\int_0^T Q_f \, dt$ is equal to the river flow is erroneous.

The error results from an incomplete use of continuity concepts which presents a continuity argument for fresh water only. Actually there are two species to which the continuity concepts apply in the estuary: the water (actually mass) and the salt. Other investigators have made this same error. An apparent reasonable argument is frequently presented along lines something like the following: A certain amount of fresh water flows into the estuary from the river. In order to maintain continuity an equal amount of fresh water must be carried through each section, and since, as one proceeds down the estuary, the salt content increases, it is evident (?) that only a portion of the volume can be fresh water, and so the seaward directed flow must increase in proportion to the decreasing fraction of fresh water. The correct application of continuity concepts recognizes that it is the mass of water on the one hand and the salt on the other that is conserved over one or more tidal cycles, not the 'fresh water.'

The mechanism can be correctly explained as follows: consider a segment of the estuary bounded by the sides, bottom, and surface, and by two cross sections, one in the fresh-water river at the head of the estuary, and the other down in the estuary proper. At any given time the sum of the river inflow through the upper section, and of the flow (either into or out of the segment, depending on the tide stage) through the lower section, will equal the rate of change of volume, accompanying the changes in tidal stage, within the segment. At the same time there will be a flux of salt through the lower segment. Under conditions of mean steady state, the integrated inflow of mass (water) into the segment through the section over a tidal period must equal the integrated outflow of mass (water) through the lower section during the same time period. Likewise, the net flux of salt through the lower section during a tidal cycle must be zero.

Neglecting molecular diffusion, the instantaneous local rate of change of the salt concentration, s, is given by

$$\partial s/\partial t = -\partial(v_1 s)/\partial x_1 \tag{10}$$

The procedure for obtaining the time mean of this equation over one or more tidal cycles has been discussed elsewhere [*Pritchard*, 1954]. For a sectionally homogeneous estuary, the time mean of the salt balance equation of one or more tidal cycles is

$$\partial \bar{s}/\partial t = -\bar{v}_1 \, \partial \bar{s}/\partial x_1 - \frac{1}{A} \frac{\partial}{\partial x_1} \left\{ A < v_1' s' > \right\} \tag{11}$$

where $\bar{v}_1$ is the mean sectional velocity averaged over one or more tidal periods, $\bar{s}$ is the mean salinity at the section over one or more tidal cycles, and $< v_1' s' >$ is the mean product of the velocity and salinity deviations resulting from the turbulent motion. This latter product is the flux of salt due to turbulent diffusion, and is classically replaced by the expression $-K_1 \, \partial \bar{s}/\partial x_1$, where K_1 is the eddy diffusivity.

Under mean steady state, $\partial \bar{s}/\partial t = 0$, and we have

$$0 = -\bar{v}_1 \, \partial \bar{s}/\partial x_1 + \frac{1}{A} \frac{\partial}{\partial x_1} \left\{ Ak_1 \, \partial \bar{s}/\partial x_1 \right\} \tag{12}$$

The mean salt balance is thus expressed by a

balance between an advective term related to the net downstream flow and a non-advective or turbulent diffusion term. The net downstream flow required to transport seaward a volume of water equal to the river flow results in a flux of salt seaward. This is balanced by a flux of salt in the opposite direction resulting from turbulent diffusion. The purely oscillatory tidal motion is an important part of the mixing mechanism in a tidal estuary since it provides the major source of the energy required for mixing.

Utilizing (9), and integrating (12), we have, to the first approximation

$$R\bar{s} - \bar{A}K_1\,\partial\bar{s}/\partial x_1 = 0 \qquad (13)$$

Thus it is not possible to deduce the river inflow into an estuary from salinity observations unless we know the appropriate mixing parameters, that is, the eddy diffusivities. At the present time our knowledge of the processes of turbulent diffusion is certainly insufficient to allow a determination of the river inflow into a tidal estuary by any means other than tedious procedure of measuring time series of current observations.

It is not surprising then that in their attempt to test their method against actual data, Todd and Lau found the observed river inflow to be nearly three times as large as the computed river inflow. The reason for this failure has nothing to do with upstream storage. The basic assumptions used by the authors are simply erroneous, and hence the results of the method cannot be expected to be correct.

It might be appropriate to point out that *Ketchum* [1950] made the same questionable assumption that Todd and Lau did when he defined a non-tidal drift (NTD) as $NTD = R/\bar{F} \times \bar{A}$. Ketchum's arguments parallel the disarmingly simple but erroneous presentation given earlier in this critique.

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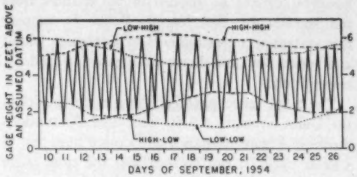

Fig. 10 – Tidal gage height at the Sacramento—San Joaquin Delta, September 10–26, 1954

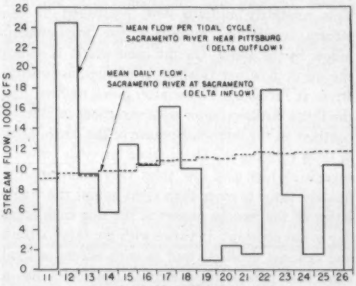
MEAN FLOW PER TIDAL CYCLE, SACRAMENTO RIVER NEAR PITTSBURG (DELTA OUTFLOW)
MEAN DAILY FLOW, SACRAMENTO RIVER AT SACRAMENTO (DELTA INFLOW)
STREAM FLOW, 1000 CFS
DAYS OF SEPTEMBER, 1954

Fig. 11 – Mean of the Sacramento river flow, September 11–26, 1954

David K. Todd and *Leung-ku Lau* (Division of Civil Engineering, University of California, Berkeley 4, Calif.; Authors' closure)—That the mechanisms of flow in tidal estuaries are complex and yet incompletely understood is amply illustrated by the above discussion. A lengthy analysis is presented of streamflow into a tidal estuary, which, although correct in itself, is based upon idealized conditions which do not necessarily occur in most large estuaries. It is unfortunate that the discusser's analysis becomes the justification for his positive statements as to the errors in our paper.

The discusser begins with the generalized equation of continuity for incompressible fluid and reduces it to

$$\frac{\partial}{\partial x_1}(Av_1) = 0 \qquad (7)$$

This equation is then expressed as

$$\int_0^T (Av_1)\,dt = R \qquad (9)$$

"providing the river flow and tidal range are considered constant." These two assumptions,

however, cannot be applied to the outflow from the Sacramento—San Joaquin Delta. To support this statement measurements of tidal-gage height and mean flow are shown in Figures 10 and 11, respectively.

The tidal range near Pittsburg at the outlet of the Delta averages 4.5 ft. The tidal fluctuations shown in Figure 10 span slightly more than half of a lunar cycle. It can be seen that the tidal range varies from one tidal cycle to another throughout a lunar cycle. In Figure 11 mean daily discharges of the Sacramento River at Sacramento are shown. This relatively uniform flow, controlled by upstream regulation, represents the predominant inflow to the Delta. On the same graph is shown the mean flow per tidal cycle of the Sacramento River at Pittsburg. These latter flows, representing the Delta outflows, show wide variations in marked contrast to the inflows. Because of the irregularity of tides entering the Delta (time intervals between successive high and low tides vary from approximately three to more than eight hours) the translation of the various phases of the tide each lunar day is not constant. It varies with the tidal pattern and channel depth as well as with effects of local wind and barametric pressure. The Delta has a water-surface area of some 40,000 ac which acts as a reservoir for storing tidal waters. The irregularity of the tides, combined with the fact that the estuary permits both ebbing and flooding to occur simultaneously, produces changes in the tidal volume from one tidal cycle to the next. These changes of water volume within the Delta produce the measured irregular outflows illustrated by Figure 11.

The effect of changing tidal volumes within the Delta on the mean outflow computed from velocity measurements near Pittsburg [*Ingerson*, 1955, see list at end of paper] were taken into account by engineers of the California Water Project Authority. Hourly gage height readings from 28 water-stage recorders in the Delta were tabulated for short periods at the start and the end of the September 1954 measurements. Each recorder was assumed to indicate water-level changes within an assigned area. The change in Delta water volume between any two times was found by algebraically summing the products of the specific areas and their respective gage height changes. By considering times of equal Delta tidal volume at the start and end of a two-week lunar cycle, tidal volumes were eliminated from the hydrologic equation and the mean flow could thereby be computed. The reported value of 7353 cfs in our paper was obtained by *Kabakov* [1955] in this manner.

From the above elaboration it follows that (9) cannot be applied to compute the Delta outflow because of the assumptions upon which it is predicated. The limitations of (1) for this purpose relate to salinity changes within the Delta as described in the paper.

We appreciate the interest shown by the discusser and hope that this reply helps to clarify the problems involved in estimating stream-flow into a tidal estuary.

Discussion of "Evidence for a Critical Wind Velocity for Air-Sea Boundary Processes"

BY HUGO MANDELBAUM

and "Change in the Relationship Between Wind and Surface Water Movement at Higher Wind Speeds"

BY A. L. LAWFORD AND V. F. C. VELEY

[*Trans.*, 37, 685–693, 1956]

Hugo Mandelbaum (Wayne State University, Detroit, Michigan, received January 28, 1957)— It seems fortunate that two papers concerning the relationship between wind velocity and movement of the surface water appeared in the same issue. Since both papers show apparently different results, it seems necessary to point out differences in the methods used to obtain these results. The first paper shows evidence for a discontinuity of the wind-water movement relationship between

wind force groups 1 to 4 and 5 to 8 of the Beaufort scale, and a *decrease* of the ratio k, current velocity/wind velocity, for stronger winds. The second paper reports an indication for a possible *increase* of this ratio at wind forces above 3 Beaufort. A comparison of both papers, therefore, is called for. Lawford and Veley do not include wind forces above Beaufort 5, and as indicated in their Figures 1 and 2, many values for force 5 are extrapolations from current curves at forces 1 to 4. If any discontinuity should occur between 4 and 5 or at higher forces, it cannot be discovered or will be veiled. Whether any change in the ratio k occurs at force 3 as indicated by the curves for VARNE and S.2 could not be detected at Amrum Bank. The method used by Mandelbaum does not permit the interpolation of intermediate values. As pointed out by Lawford and Veley, the conversion of wind velocities estimated by the Beaufort scale to a unit scale of cm/sec or mi/hr is always inherently arbitrary. This conversion scale also depends on where the wind velocity is estimated, at the masthead; on deck of the vessel, three to four meters above the water surface; or directly at the water surface. As indicated by Mandelbaum (Fig. 1) the various attempts for such conversions differ greatly from each other. A slightly different position given to forces 4 and 5 might alter the appearance of the curves completely. The results of both papers have this same inherent uncertainty.

It should also be pointed out that the water transport used in comparison with the wind velocity is not the same in both papers. At the German lightship a chip log is used to determine the current velocity. Hence values given are surface velocities of the current. The current layer to which the observations on the English lightships refer is four to five meters below the surface. Both values, of course, are not strictly comparable.

I might mention also another point which has to be considered in evaluation of the evidence for an increased current speed at velocities higher than Beaufort 3. It has been pointed out [*Mandelbaum*, 1955] that currents at winds that changed during the last four hours preceding the observation produce current velocities of approximately 30 pct less than those at winds which blew steadily from the same direction during the last four hours. Wind steadiness is much greater at wind forces 3 and 4 than at very gentle breezes. This would cause curves to become steeper for the higher velocities.

The complexity of the problem merits the attempts for its solution coming from different angles of approach and different methods used in both papers.

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MANDELBAUM, H., Wind-generated ocean currents at Amrum Bank Lightship, *Trans. Amer. Geophys. Union*, **36**, 72–86, 1955.

A. L. Lawford and V. F. C. Veley (National Institute of Oceanography, Wormley, nr. Godalming, Surrey, England, received April 15, 1957)—Mandelbaum's comments sum up the differences between and the similarities in the two papers so succinctly that we can add little under these counts.

There are however a few points in his method of analysis which we could criticize, notably his selection of winds between S and W in his investigation and the interpretation of his Figure 1 (reprinted on next page), but where there is so little certainty different investigators will obviously often use different and arbitrary methods. We do not doubt that Mandelbaum can find equally valid criticism of parts of our methods.

Turning to his Figure 1, the evidence for the discontinuity seems to rest on one point (Beaufort 4) since it is possible to draw a reasonably straight line through the points representing Beaufort 2, 3, 5, 7, and 8. Figure 5 is a redraft of Mandelbaum's figure using Verploegh's scale and including the origin, which is another point on the curve. Thorade's parabola might be said to pass through Beaufort 0, 1, 2, and 3; omitting Beaufort 4, the curve seems linear for Beaufort 3 to 8. Now Mandelbaum's Table 1 shows that SSW winds produce stronger currents than do either SW or WSW winds. It seems to us that the values of **R** in his Table 3 might be greatly affected by the percentage distribution of these winds for each wind strength. Beaufort 4, for example, might contain a high proportion of SSW winds, in which case its R would be high compared with that for another strength which contained mainly WSW winds. In such a case the Beaufort 4 point could be considered as invalid.

Referring to his Table 5, we are at a loss to ascribe any meaning to the constant c in the equation $V = kW + c$, since both periodic terms and residual current at calms have been extracted from the water movement and therefore only

wind-induced current remains. Thus when $W = 0$, $V = 0$; this is taken account of in our tentative redrawing where a parabola of the form $V = k\sqrt{W}$ might be said to pass through the origin in Figure 1 of Mandelbaum.

The Beaufort conversion scale used in our analysis was taken from *Great Britain, Meteorological Office* [1939] and corresponds with none of those used by Mandelbaum.

The analysis referred to in the last paragraph of our paper is now in hand, and it is hoped in due course to publish the results for up to twelve lightships.

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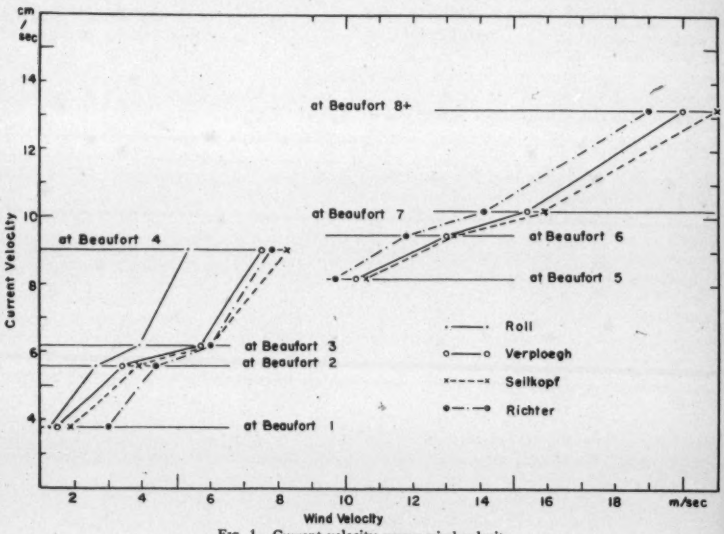

Fig. 1 – Current velocity versus wind velocity

Reviews, Abstracts, and Bibliography

Reviews and Abstracts

WALTER J. SAUCIER, *Principles of Meteorological Analysis*, University of Chicago Press, xvi + 438 pp., 1955, $10.

This is a comprehensive treatment of meteorological analysis which should serve as a useful reference book for those concerned with almost any aspect of analysis in extratropical latitudes. It is especially recommended for the library of the meteorologist who devotes a major part of his time to analysis and also of the analytical research worker who is likely to refer to many of the more obscure subjects treated here. As a text for training meteorologists in analysis it achieves some of the aims mentioned by Saucier in his preface, particularly in regard to a greater emphasis on flow in the free atmosphere and its integration with analysis of flow in the lower levels. However, there is much detail in many places throughout the book and only the meteorological student specializing in analysis will be amply rewarded for the time spent in reading this text with any degree of thoroughness. In view of the current trends toward centralization of analysis and forecasting and the growing role of the electronic machine in performing these functions objectively, it becomes questionable whether, in the training of the average meteorologist, sufficient time can or should be devoted to the many details of analysis treated in this text.

Naturally the book abounds with much useful information on analysis as well as the mechanics, statics, and thermodynamics of the atmosphere and even forecasting, although the latter is not stressed. Some of these subjects are discussed more interestingly and practically than in many earlier texts. Among the topics which receive excellent treatment are the basic problems of analysis in Chapter 4, graphical analysis in Chapter 5, analysis of contours on constant pressure charts with emphasis on geostrophic wind, thickness patterns, and vertical variation of flow with height in Chapter 7, analysis of the surface chart with emphasis on consistency with flow aloft in Chapter 9, and isotach, isogon, and streamline analysis in Chapter 10. On the other hand, portions of the text which suffer especially from the redundancy mentioned above are Chapter 3 on hydrostatics and static stability, Chapter 6 on cross-section analysis, and the bulk of Chapter 10 where divergence, vorticity, and deformation are treated. Also, even in some shorter chapters, such as Chapter 11 which treats broad-scale analysis, there is repetition of material that is treated in other portions of the text.

To a great extent this book suffers by its appearance on the meteorological scene approximately five to ten years too late since the numerical era is now bringing sweeping changes to the whole field of synoptic meteorology. As a result, meteorological training in the field of analysis and forecasting is going through a major transition which will probably continue for the next several years. Thus, much of the emphasis and even the general organization of the text may need considerable alteration if it is to be used in intermediate analysis courses. Although we could not have expected the author to predict the radical impact of the electronic machine in the past few years, it is surprising that he did not at least anticipate it to some extent. For example, there is no treatment of objective analysis of meteorological data, which was already being seriously considered in the 1940's and is now being used operationally in the Joint Numerical Weather Prediction Unit.

JAY S. WINSTON

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Notes and Personalia

Notes

CORRIGENDA—In the paper by J. R. Philip and D. A. de Vries in the April 1957 issue of the *Transactions*, pages 222–232, the following corrections are noted. On page 224, in Eq. (7), the symbol ρ should be eliminated from the left-hand term so that this reads

$$q_{vap}/\rho_w = -D_{Tvap}\,\nabla T - D_{\theta vap}\,\nabla\theta$$

On page 227, Eq. (15) should read

$$-(a+\theta)\,D_{atm}\,\nu h\beta(\nabla T)_a = -\rho_w D_{Tvap}\nabla T$$

On page 231, Eq. (24), should read

$$C\frac{\partial T}{\partial t} = \nabla\cdot(\lambda\nabla T) + L\rho_w\nabla\cdot(D_{\theta vap}\nabla\theta)$$

On page 245 of the April 1957 issue of the *Transactions*, the a in Eq. (1) of the paper by B. D. Aggarwala and Edward Saibel should be a coefficient to the radical rather than the root as now indicated.

NATIONAL SCIENCE FOUNDATION SCIENCE FACULTY FELLOWSHIP AWARDS—Applications for a second group

of science faculty fellowship awards are being received by the National Science Foundation up to September 3, 1957. Fellowships are offered as a means of improving the teaching of science in American colleges and universities. Announcement of the awards will be made about the middle of October. The fellowships are open to United States citizens who hold baccalaureate degrees or equivalent, have demonstrated ability and special aptitude for science teaching and advanced training, and have taught at the college level as full-time faculty members for not less than three years and intend to continue teaching. The Foundation's award will be adjusted so that the combined support from the Foundation and other sources will not exceed $10,000 per annum plus travel and certain other expenses, with full tuition paid by the Foundation. Interested persons should get into touch with the Division of Scientific Personnel and Education, National Science Foundation, Washington 25, D. C.

NATIONAL SCIENCE FOUNDATION PROGRAM IN POSTDOCTORAL FELLOWSHIPS—Applications will be accepted through September 3, 1957, by the National Science Foundation for the second group of postdoctoral fellowships of 1957 in both the senior postdoctoral and regular postdoctoral programs. Announcement of the successful candidates will be made in mid-October. To be eligible for these awards, candidates must be citizens of the United States with special aptitude for advanced training and must hold the doctoral degree or have the equivalent in training or experience. Five years' experience beyond the science doctorate is necessary to qualify for the senior postdoctoral program. Annual stipends to a maximum of $10,000 will be adjusted to match closely the regular salaries of award recipients under the senior program plus a limited allowance to aid in defraying travel expenses. The regular program awards carry a stipend of $3800 per year plus allowances including tuition and fees. Interested persons should write to the Division of Scientific Personnel and Education, National Science Foundation, Washington 25, D. C.

NEW PUBLICATION IN MINING AND METALLURGY—Volume 1, Number 1, of *The Japan Science Review* covering mining and metallurgy for the half year October, 1955 to March, 1956 has been published in Japan, this being a series of bibliographic items forming: Part I, a title list; Part II, abstracts; and Part III, reviews. The price per issue is $1.50. Subscriptions and other inquiries should be sent to the Managing Secretary, Iron and Steel Institute of Japan, 10, 2-chome, Marunouchi, Chiyoda-ku, Tokyo, Japan.

NEW MODEL OF SAN FRANCISCO BAY—The Corps of Engineers recently dedicated an acre-sized working hydraulic model of San Francisco Bay as a major tool in the comprehensive investigation of the San Francisco Bay area. The purposes and problems are numerous, but among these are to determine the feasibility of salt-water barriers in the Bay and to determine remedial measures that can be taken against deposits of sediment in ship channels. The problems also to be investigated include flood control, water supply, development of fresh-water lakes, shore-line transformation, and land reclamation.

INTENSIVE GLACIAL STUDY IN THE USSR—The Uzbekistan Academy of Sciences has organized an expedition to the Fedtchenko Glacier on the Pamir Plateau in connection with the USSR program for the International Geophysical Year. One station is to be established at Yazgoulem Pass at an altitude of 16,000 ft, another at the foot of the Pass somewhat lower down, with a third as a hydrometeorological station at an altitude of about 13,000 ft.

AMS STATEMENTS ON WEATHER PROBLEMS—The American Meteorological Society has adopted a policy of issuing statements to be reviewed annually on weather problems of great interest to the public. These are aimed to serve as a guide to those interested in an unbiased appraisal of the particular meteorological problem. Statements of this nature have recently been issued concerning cloud seeding, weather forecasting, and the detection and tracking of tornadoes. With regard to forecasts, their recent statement notes that forecasts for periods of more than a month in advance are sometimes attempted, as, for example, that the season will have abnormally high temperature or precipitation. The success of this type of forecast has not yet been demonstrated, and such forecasts must be considered experimental. The position is that individuals or organizations that publish forecasts for conditions more than one month in advance mislead the public if they do not clearly describe the forecast as experimental and of unproven value. The Society also holds that the issuance of detailed day-by-day forecasts for more than two or three days in advance is misleading and not justified by present-day meteorological knowledge.

SCRIPPS EXPEDITION TO THE NORTHEAST PACIFIC—Expedition MUKLUK of the Scripps Institution of Oceanography is now in progress in the area ranging across the northeast Pacific through the Gulf of Alaska to the southeastern corner of the Bering Sea, using Research Vessels *Spencer F. Baird* and *Horizon*. George G. Shor, Jr., is scientific leader of the expedition. The work will cover deep current measurements, the physical properties of water, seismic studies, bottom temperature gradient, bathymetry, coring, sea water chemistry, sediment chemistry and mineralogy, and other studies incidental to this work.

MEETINGS OF THE WORLD METEOROLOGICAL ORGANIZATION—The Commission for Aerology met in Paris, June 18–July 9, with Joe R. Fulks as Chief of the U. S. delegation, Henry G. Houghton and Karl R. Johannessen as delegates, and Jack Thompson as advisor. The Commission on Instruments and Methods of Observation met during the same period. Chairman of the U. S. delegation was Christos Harmantos, with Donald Swingle and U. S. Hardin as delegates, and Vaughn Rockney as advisor.

COASTAL ENGINEERING CONFERENCE—The Sixth Conference on Coastal Engineering will be held at the University of Florida at Gainesville, December 2–7, 1957. Interested persons should write to the College of Engineering at the University of Florida or to the Secretary, J. W. Johnson, of the University of California at Berkeley.

MEETING OF THE DIVISION OF FLUID DYNAMICS OF THE AMERICAN PHYSICAL SOCIETY—The Tenth Meeting of this Division will be held at Lehigh University, November 25–27, 1957. Interested persons should address the Program Chairman, F. N. Frenkiel, Applied Physics Laboratory, Johns Hopkins University, Silver Spring, Maryland.

MEETING OF THE SOCIETY OF EXPLORATION GEOPHYSICISTS—The Twenty-Seventh Annual Meeting of the Society of Exploration Geophysicists will be held in Dallas, Texas, November 11–14, 1957. Interested persons should get into touch with the Society's office, P. O. Box 1536, Tulsa 1, Oklahoma.

INHIBITING EVAPORATION FROM WATER SURFACES—An Australian scientist, W. W. Mansfield of the Commonwealth Scientific and Industrial Research Organization, has developed a method to decrease evaporation from water surfaces by using beads of hexadecanol, that is, from a very thin film which oxygen and rain can penetrate. The chemical has no effect on fish or other forms of aquatic life, nor on the use of water for drinking purposes. It is currently being used in small reservoirs or tanks for farm purposes.

NEW ACADEMIC RECOGNITION FOR HYDROLOGY—The Imperial College of Science and Technology of the University of London has recently established a Readership in Hydrology in recognition of that subject as a separate scientific discipline. There will be instruction both at the graduate and undergraduate levels, and research will be actively pursued. Peter O. Wolf has been appointed Reader in Hydrology.

Personalia

CHARLES F. BROOKS, Professor of Meteorology at Harvard University and Director of the Blue Hill Meteorological Observatory, has recently retired.

DEAN S. CARDER, Chief of the Seismology Branch of the U. S. Coast and Geodetic Survey, has been awarded the Colbert Medal of the American Society of Military Engineers for outstanding achievement in the development and application of seismological techniques to the detection and evaluation of ground disturbances of critical importance to military operations.

HENRY C. CORTES, Vice President and Director of the Magnolia Petroleum Co., was awarded the Honorary Degree of Doctor of Science by the University of the South.

E. A. ECKHARDT, formerly Vice President in charge of Research for the Gulf Research and Development Company, has been appointed Assistant Director of the National Science Foundation for the Division of Mathematical, Physical, and Engineering Sciences. Raymond J. Seeger, who has been serving as Acting Assistant Director will continue as Deputy Assistant Director of the Division.

JAMES J. GERAGHTY, Ground-Water Geologist and Hydrologist, has organized a new firm of Consulting Ground-Water Geologists in New York City under the name of Geraghty, Miller and Hickok.

ROSS GUNN, Director of Physical Research of the U. S. Weather Bureau, has been designated the recipient of the Robert M. Losey Award of the Institute of Aeronautical Sciences "in recognition of outstanding contributions to the science of meteorology as applied to aeronautics."

GAIL A. HATHAWAY, Consultant with the International Bank for Reconstruction and Development, recently attended the World Power Conference in Belgrade, Yugoslavia.

W. A. HEISKANEN of the Institute of Geodesy, Photogrammetry, and Cartography at Ohio State University has been awarded an honorary degree of Doctor of Engineering by the University of Bonn.

J. A. JACOBS, Professor of Geophysics at the University of Toronto and Secretary of the Canadian Committee on Arrangements for the Eleventh General Assembly, IUGG, will take up duties at the University of British Columbia at Vancouver in September.

ROBERT B. HICKOK has left his duties with the Agricultural Research Service of the Department of Agriculture and has taken up duties with the engineering firm of Holmes and Narver, Inc. of Los Angeles.

OWEN S. LEE has left his work with the Division of Oceanography of the U. S. Hydrographic Office and taken up duties with the Arctic, Desert, Tropic Information Center of the Research Studies Institute of the Air University Command at Maxwell Air Force Base, Alabama.

JOE WEBB PEOPLES, who has been on duty with the International Cooperation Administration in the Philippines for the last two years, is returning to his regular duties as Professor of Geology at Wesleyan University.

FRANK PRESS has been named to succeed Beno Gutenberg as Director of the Seismological Laboratory of the California Institute of Technology. Gutenberg, who has been with the Laboratory since 1930, will continue as Professor of Geophysics.

WALDO L. SCHMITT, Marine Oceanographer, Curator for the Smithsonian Institution for many years, and formerly Secretary and Vice President of the Section of Oceanography, AGU, recently retired.

ALLEN H. SCHOOLEY has returned to his position as Superintendent of the Electronics Division of the Naval Research Laboratory after serving a year as Advisor to the Brazilian Navy in matters relating to the establishment of a Brazilian Naval Research Institute.

W. TAYLOR THOM, Professor Emeritus of Geological Engineering at Princeton University, was awarded a medal by the American Institute of Geonomy and Natural Sciences for outstanding contributions to science in the art of living.

F. A. VENING MEINESZ of The Netherlands was recently honored on the occasion of his 70th birthday by a special meeting of the Geophysical Section of the Royal Netherlands Geological and Mining Society for his outstanding work in geophysics. A volume of essays and papers had been prepared for this commemorative event that includes contributions from prominent geophysicists all over the world. He was named the Ninth Recipient of AGU's William Bowie Medal in 1947.

ABEL WOLMAN has recently retired as Professor of Sanitary Engineering at Johns Hopkins University. He will, however, continue duties as Chairman of a special committee studying educational objectives of the School of Hygiene and Public Health and many of his other activities in relation to various boards and committees.

WARREN S. WOOSTER, Assistant Research Oceanographer at Scripps Institution of Oceanography, is on a year's leave from Scripps to direct the marine research program of the Republic of Peru with headquarters at Lima. While his task will be to organize and direct the new research program, his first oceanographic study will be of the northern boundary of the Peru Current where most of the tuna fishing in South American waters is done. He will also study El Niño, a warm current from the north which occasionally flows down the Peruvian coast and causes death to many birds and fishes.

EUGENE F. BANGS, Development Engineer for the Aero Service Corporation in Philadelphia, died June 22, 1957, at the age of 41. He was born at McAlester, Oklahoma, and attended Oklahoma A and M College. Upon the completion of his studies, he entered on duties with the Spartan School of Aeronautics and in 1947 took up duties with the Geophysical Development Corporation and subsequently with the Frost Geophysical Company. He had devoted much of his life to the development of geophysical instruments, especially airborne instruments, and at the time of his death he was working on improvements for Shoran measurements. He had been a member of AGU since 1949.

CHARLES E. DEPPERMANN, Jesuit scientist of Manila Observatory, died in Manila on May 8, 1957, at the age of 68. He was born in New York. He took his master's degree from Woodstock College in 1918 and his doctorate from Johns Hopkins University in 1925, and studied subsequently at the University of California and St. Louis University. He devoted most of his adult life to work in the Philippines, beginning his service as Chief of the Seismological Division in the Philippine Weather Bureau in 1926. He became Director in 1946 and his recent years were spent in rebuilding the observatory at Baguio, devoting an increasing amount of his efforts to seismology. He had been a member of AGU since 1934.

RAFAEL GARCIA-RODRIGUEZ, Director of the Spanish Institute of Oceanography, died in Madrid, March 5, 1957.

PAUL LOVERIDGE HESLOP, of Portland, Oregon, died November 7, 1956 at the age of 65. He was born at Unadilla, New York. In 1914 he took his baccalaureate degree from Cornell Uuiversity. His entire career was devoted to the study of hydraulics and hydro-electric projects, including studies of stream flow and spillway design. During the first World War he served in the United States Army, following which he undertook work in Colombia for Charles B. Hawley and Company, later entering into duties with United Engineers and Constructors. In 1929 and 1931 he was with Electric Bond and Share Company and subsequently spent considerable time on the Bonneville Power Project on the Columbia River. He worked with the Corps of Engineers from 1933 to 1940 and resumed work with Electric Bond and Share Company in 1941. Subsequently he became consultant on construction for Cia. Auxiliar de Empresas Eletricas Brasileiras, from which work he retired in 1956. He had been a member of AGU since 1940.

JUAN JAGSICH, Professor of Geodesy of the University of Cordoba, Argentina, died April 3, 1956, at the age of 69. He was born at Sopron, Oszlop, Hungary and took his baccalaureate degree at the National Technical College at Sopron in 1905. He took a degree as Diplomatic Agricultural Engineer from the Polytechnic Institute of Zurich in 1909. He undertook his duties at the University of Cordoba starting in 1918 and in that period had not only taught topography, cartography, geodesy, and practical astronomy but some work in meteorology and other aspects of geophysics as well. He became a member of AGU in 1954.

PAUL S. KRAUS of the California Texas Oil Company died November 11, 1956, in Washington, D. C., at the age of 50. He was born in Kansas City, Missouri, and secured his education at the University of Missouri. Upon his graduation, he went into geological work undertaking duties for the Standard Oil Company of California before joining the California Texas Company. He had spent a good deal of time in recent years in Indonesia. At the close of World War II, it was he and his intelligence group that captured Hideki Tojo, Premier of Japan. He had been a member of AGU since 1952.

HERBERT ROLLO MORGAN, Principal Astronomer at the Naval Observatory, retired, died in Washington, D. C. on June 11, 1957 at the age of 82. He was born at Medford, Minnesota, and took his bachelor's, master's, and doctor's degrees from the University of Virginia, following which, in 1901, he entered the service of the Naval Observatory, in which service he continued until his retirement in 1944. Following his retirement, he took up duties as Research Associate at Yale; and during his many years of active work, he engaged in numerous related activities including a term as Director of the Morrison Observatory. He had been a member of AGU since 1932.

JOHN WALLER PRITCHETT of the Texas State Board of Water Engineers, retired, died April 19, 1954, according to belated word received. He was born in Glasgow, Missouri in 1882, and studied at Houston State Teachers College. In 1906, he was given a professional degree in Civil Engineering by the University of Texas. His early work included service with various railroads and other utilities in the United States and in Mexico and service with various local and state governmental groups. In 1912 he entered the service of the State Surveyor and in 1918 began duties with the Texas State Board of Water Engineers, of which Board he was a member from 1936 until his retirement in 1952. He had been a member of AGU since 1935.

JOHN CHARLES RABBIT, Geologist of the U. S. Geological Survey, died June 10, 1957, at the age of 49. He was born in Butte, Montana, took his baccalaureate degree from Montana School of Mines in 1935 and his Master of Science degree in 1937. He took his doctorate at Harvard in 1947. Before taking up duties with the U. S. Geological Survey, he was in the service of the Montana State Bureau of Mines and Geology; and while studying at Harvard, he was an Assistant in the Department of Mineralogy and Petrography. He entered the service of the Geological Survey in 1942. He had been a member of AGU since 1947.

WILLIAM HENRY TWENHOFEL, Professor of Geology at University of Wisconsin, retired, residing in Orlando, Florida, died January 7, 1957 at the age of 81. He was born in Covington, Kentucky. He took his baccalaureate degree from National Normal University in 1904 and another from Yale in 1908. He also took his Master's degree and Doctor's at Yale in 1910 and 1912, and was awarded an Honorary Doctorate at the University of Louvain in 1947. He began his professional career as a teacher at East Texas Normal College in 1904. From 1910 to 1916 he was Professor at the University of Kansas. He took up his duties at the University of Wisconsin in 1916 where he continued until he retired in 1945. Subsequently he served as Visiting Professor at Yale and the University of Tulsa. In addition to his regular duties, he was the Editor of the *Journal of Sedimentary Petrology* and Associate Editor of the *American Journal of Science* for many years. He had been a member of AGU since 1931.

Union, Section, and Committee Activities

Minutes of Executive Committee Meeting, American Geophysical Union

First Session, April 28, 1957

The meeting was called to order at 14h 00m in the Board Room of the National Academy of Sciences—National Research Council Building, 2101 Constitution Avenue, Washington, D. C., by President Maurice Ewing.

Present—Thirty-four persons were present as follows: P. H. Abelson, L. H. Adams, John N. Adkins, L. T. Aldrich, K. Hilding Beij, L. V. Berkner, J. J. Capello, P. E. Church, Frank L. Culley, Earl G. Droessler, Maurice Ewing, R. E. Gebhardt, N. C. Gerson, Beno Gutenberg, H. H. Hess, Albert J Hoskinson, B. F. Howell, Jr., W. C. Jacobs, H. R. Joesting, J. W. Joyce, H. E. Landsberg, Ray K. Linsley, Thomas F. Malone, James H. Nelson, James A. Peoples, Jr., John C. Reed, R. R. Revelle, A. N. Sayre, J. F. Schairer, M. O. Schmidt, Waldo E. Smith, E. H. Vestine, H. G. Wilm, and G. P. Woollard.

Approval of minutes—The minutes of the Executive Committee meeting held on November 17, 1956, published in the February 1957 issue of the *Transactions* (pp. 135–145), were approved.

General Secretary's Report

The last report of the General Secretary recorded the minutes of the Executive Committee meeting of November 17, 1956, and was published in the February 1957 issue of the *Transactions* [pp. 135–138].

Publications—The following issues of the *Transactions* have been printed and distributed since our last meeting:

December 1957: 147 numbered pages and 21 unnumbered pages including 10½ pages of paid advertising; edition of 6200

February 1957: 145 numbered pages and 19 unnumbered pages including 13½ pages of paid advertising; edition of 6300

The April 1957 issue is about ready for distribution late in April. The printer has been somewhat slow in making delivery due, he says, to extreme busyness in their plant. The April issue will contain 141 numbered pages plus 90 numbered pages in the Directory plus 33 unnumbered pages including 16¾ pages of paid advertising.

The Editorial and Publication Committee has met regularly at bimonthly intervals and is scheduled to meet again on May 9. Walter B. Langbein, who had been a member of this Committee since its organization in 1945, resigned as a Committee member and has been replaced by Thomas Maddock, Jr. During the 12 years of his membership on the Committee, Langbein has made outstanding contributions to the development of the format, the improvement of papers, and has helped in various ways in addition to taking care of the formal duties as editor. During most of this time Langbein has not accepted his honorarium of $150 per year to which he is entitled for his editorial work, but has requested that it be added to the Permanent Fund. Besides its editorial duties the Committee has considered not only problems of the *Transactions* but problems of other publications, including the Russian translation project for which we have received a grant from the National Science Foundation, and the Monograph Series.

Mrs. W. A. James of New Haven, Conn., our Advertising Representative, says that the advertising in the June issue probably will be lower than for the issues earlier this year. A new Committee on Advertising has been appointed under the Chairmanship of N. C. Gerson in an effort to help develop contacts for Mrs. James. A number of advertisers have continued their contracts through a year and then discontinued, and certain others that seemed like rather obvious prospects have not placed advertisements. Any suggestions or assistance that can be given to this effort will be greatly appreciated.

Negotiations with the Johnson Reprint Corporation have been completed for reprinting the out-of-print numbers of our *Transactions*, the sale of our back stock prior to 1954, and for the annual transfer of numbers more than 2½ years old. The *Transactions* for 1954 will be turned over to this company as of July 1, 1957.

Sales of Geophysical Monograph No. 1 have continued at the rate of about one a day. As the project has now liquidated itself, the accumulated funds provide a small margin for the publication of Monograph No. 2. This is not an adequate way of financing the monographs. We have been seeking a fund of $50,000 to $100,000 to set up as a revolving fund so that monographs that should be published can be published without too much concern of the economic factors involved. Suggestions for obtaining funds for this purpose are invited.

We have received a grant of $22,400 from the National Science Foundation to cover two phases of the Russian translation project. These two phases are: (1) the translation and publication of *Izvestiia* (Geophysics Series) and (2) the review or survey of *Trudy* (of the Geophysical Institute) to see what should be identified as special translation projects. The Pergamon Press will do the translation and publication of *Izvestiia* (Geophysics Series) and will offer it for sale. The project will be subsidized from our National Science Foundation grant during the first year. The sales will be credited to the account, with a limited per-page payment from the grant. An Editorial Board is being established to work with Pergamon Press on this. However, the Pergamon Press has proceeded to

develop a format in advance of the formal assurance that the grant would be forthcoming. The Editorial Board will consider the format that the Pergamon Press is developing upon receipt of the first issue and arrange for appropriate modifications, if needed, and will also guide the actual work relative to *Trudy*. The third phase of the project, namely, the translation of abstracts relating to geophysics from the Iron Curtain countries, is in a state of advanced study at the National Science Foundation, and a grant is anticipated soon. In this connection, it is planned to survey the needs of American geophysicists for translations from the Russian literature in order that we may be guided appropriately in subsequent years.

Appointment of committees—A number of the committees for the current triennium have been organized, and others are being appointed. The following Standing Committees are now complete:

International Participation: J. W. Joyce (Chairman), Leason H. Adams, Lloyd V. Berkner, Walter H. Bucher, Perry Byerly, F. W. Reichelderfer, Maurice Ewing (ex-officio), A. Nelson Sayre (ex-officio), Waldo E. Smith (ex-officio)

Statutes and By-Laws: K. Hilding Beij (Chairman), Walter B. Landbein, Charles A. Whitten

Budget: John C. Reed (Chairman), Ervin H. Bramhall, Louis O. Quam

Audit: A. G. McNish (Chairman), E. B. Roberts, R. H. Weightman

Editorial and Publication: A. Nelson Sayre (Chairman), Waldo E. Smith (Secretary), Harold W. Fairbairn, George T. Faust, David G. Knapp, John Lyman, Thomas Maddock, Jr., Conrad P. Mook, Tor J. Nordenson, Frank Press, and Erwin Schmid

The following appointments to Standing Committees have been made; other appointments are pending:

Membership: Earl G. Droessler (Chairman), Elliott B. Roberts (on government memberships), Benjamin F. Howell, Jr. (on university memberships), W. E. Hiatt (on membership admissions); W. B. Foster (on brochures).

Meetings: Philip H. Abelson (Chairman)

Nominations: Leason H. Adams (Chairman)

The following Special Committees are now complete:

Resolutions: John N. Adkins (Chairman), K. O. Emery, Norman Haskell, Hatten S. Yoder

Award of the William Bowie Medal: Walter H. Bucher (Chairman), Leason H. Adams, Beno Gutenberg

Geophysical and Geological Study of Continents: George P. Woollard (Chairman), Francis Birch, William E. Bonini, Ross Gunn, Sigmund Hammer, J. B. Hersey, B. F. Howell, Jr., Patrick M. Hurley, M. J. S. Innes, Henry R. Joesting, Gordon G. Lill, L. L. Nettleton, Donald A. Rice, Howard Tatel, J. Lamar Worzel

Cosmic-Terrestrial Relationships: E. H. Vestine (Chairman), Walter Orr Roberts (Vice Chairman), R. N. Bracewell, J. W. Chamberlain, C. T. Elvey, J. W. Evans, H. Friedman, S. Fritz, H. K. Kallmann, S. A. Korff, R. R. McMath, M. G. Morgan, H. Odishaw, C. E. Palmer, A. H. Shapley, S. F. Singer, J. A. Smagorinsky, T. L. Skillman, A. H. Waynick, F. L. Whipple, H. C. Willett

Relationship of AGU to International Geophysical Year: N. C. Gerson (Chairman), Jule G. Charney, Earl G. Droessler, E. R. Piore, R. R. Revelle, M. A. Tuve, J. A. Van Allen, J. Tuzo Wilson

The following Special Committees are being formed but are not complete:

Award in Terrestrial Magnetism and Electricity: William B. Agocs (Chairman), Ross Gunn, Nelson C. Steenland

Tellers: James H. Nelson (Chairman)

Advertising: N. C. Gerson (Chairman), Karl Dyk

Relations of AGU with American Geological Institute: Appointments pending

The following Regional Committees elected by the respective regional groups are complete:

North Central Regional Committee: Alvin G. Anderson, Edward M. Brooks (Chairman), C. Robert Elford, Russell G. Mann (Secretary-Treasurer), Everett V. Richardson, Tarmo Waara

Pacific Northwest Regional Committee: Franklin I. Badgley (Secretary-Treasurer), Clifford A. Barnes (Chairman), Norbert H. Leupold (to become Chairman July 1, 1957), Fred Natella, Milton S. Sachs, Vail P. Schermerhorn, Wilbur D. Simons

Pacific Southwest Regional Committee: Representing Section of Meterology—Eugene N. Bollay, R. Corday Counts, Jr. (Secretary of Committee), Robert E. Holzer; representing Section of Hydrology—Harlowe M. Stafford, David K. Todd, Vito A. Vanoni (Chairman of Committee)

Mid-Pacific Region (Geophysical Society of Hawaii): H. Dean Parry (President), William Crawford (Vice President), Thomas S. Austin (Secretary-Treasurer), James F. McGary, George Yamanaga

The following will serve as representatives of AGU:

American Association for the Advancement of Science, Representatives on the Council: A. Nelson Sayre, W. C. Krumbein

American Geological Institute: Board of Governors—Henry R. Joesting, another to be named; Government Relations Committee—Paul L. Lyons

American Standards Association, Committee Y-15: William C. Hendrix

National Research Council, Division of Earth Sciences: H. H. Hess

National Research Council, Division of Physical Sciences: Still to be named (L. T. Aldrich subsequently named)

U. S. National Committee for the International Geophysical Year: N. C. Gerson

Membership—Membership data are:

Membership as of November 6, 1956	4969	
Reactivated	1	
New members, November 6, 1956 to April 18, 1957, including 29 applications now being processed toward membership	114	5084
Resigned	76	
Inactive	6	
Dropped	11	
Deceased (reported since November 17, 1956)	11	104
		4980

During the last few months the new members that we have received have been largely the results of the follow-up of suggested names received from members by retiring Chairman of the Membership Committee, W. E. Hiatt, plus spontaneous applications. These have just been sufficient to maintain a balance with the losses because of resignations, deaths, and so on.

The new Membership Committee under the chairmanship of Earl G. Droessler is now organizing plans for a concerted effort not only with respect to regular members but corporation and student members as well.

Dues Unpaid—As of April 19, 1957, the following dues were unpaid:

Owe for 1957	790
Owe for part of 1957	21
Owe for 1956 and 1957	194
Owe for part of 1956 and all of 1957	13
Owe for 1955, 1956, and 1957	157
Owe partly for 1955, and for 1956 and 1957	7

Deaths—The following 11 deaths have been reported to the Union office since our last meeting: G. M. Lees, January 25, 1955; George B. Lamb, September 20, 1956; Walter B. Zerbe, November 8, 1956; P. S. Kraus, November 10, 1956; Hugh C. Mitchell, November 20, 1956; Nathan C. Grover, November 29, 1956; Everette L. DeGolyer, December 14, 1956; Irvin H. Althouse, January 8, 1957; George Davis Louderback, January 27, 1957; Leon Sherman, March 2, 1957; Hal P. Bybee, March 30, 1957.

Finances—Below is a brief statement of our assets as of April 1, 1957, showing a comparison with the last two years.

	April 1, 1957	April 1, 1956	April 1, 1955
Cash balance	$32,732	$30,424	$24,459
Permanent Fund	13,741[a]	12,834[a]	11,573[a]
Emergency Fund	1,000	1,000	1,080
T. M. and E. Award Fund	1,268	985	465
	$48,741	$45,243	$37,577

[a] Does not include accumulated interest on $2,368 of U. S. Savings Bonds.

The balance at this time of the year is large because most of our income for the year has been received and a relatively small part has been spent. Therefore, the current balance is somewhat misleading.

At the end of the fiscal year on June 30, 1957, a financial statement for the year will be prepared and transmitted to the Auditing Committee. Even on June 30 our balance conveys a somewhat erroneous impression for the reasons cited above.

Office staff and jobs—Mrs. Ellen Woo (nee Lui), who was with us since last June, recently resigned to return to her home in Taiwan. The job is still open, and we are looking for a replacement. Glenda Quinn is still on a part-time basis while continuing her studies at George Washington University. She will be with us full time for a few months again this summer. Mrs. Ethel G. Sanders took up duties with us as a clerk-stenographer on November 30, 1956. Under the work and study arrangement of Antioch College we have had the services of Barbara Mills from January through March and currently have the services of Christy Webb. While these persons are employed on an hourly basis as clerk-typists, we try to give them special training and insight into office operations. James J. Capello and Waldo E. Smith complete the present complement of staff members excepting for a high school student who comes in each day to fill orders and other miscellaneous work as an office boy and the occasional hourly employment of other high school students on special projects such as mailing of the program and the *Transactions*.

Quarters—Our quarters, consisting of five rooms in the new building of the American Association for the Advancement of Science at 1515 Massachusetts Avenue, N. W., are proving adequate for our present needs and in general are very satisfactory.

International matters—There is to be a meeting of the Committee on International Participation on the morning of April 28. The Committee met formally on March 22, 1957, to consider various problems in connection with the coming Toronto meeting and other matters. Early in April the Chairman of the Committee, J. Wallace Joyce, who is also a member of the Policy Committee of IUGG, went to a meeting of the Policy Committee in Paris and will undoubtedly have a good deal to report at our meeting.

The Canadians are anxious for a large delegation from the United States to attend the triennial assembly of the IUGG in Toronto in September and are tentatively counting on about a thousand including family members. While the present list is far short of that number, at the request of the Canadian Committee on Arrangements a half-page advertisement has been placed in the April issue of the *Transactions*, and it is the plan of the Canadians to circularize the entire U. S. membership of AGU in this regard. In connection with the meeting in Toronto and the designation of delegates, President Ewing wrote to the presidents of various societies and similar groups interested in geophysics requesting suggestions as to how their field of geophysics might be appropriately represented at Toronto.

Meetings—The Pacific Southwest Regional Group held its annual meeting in Sacramento, February 14–15, 1957, with 209 registered. Concerted plans are under way to try to broaden the base of this meeting in subsequent years beyond what is now chiefly hydrology. The Chairman of the Regional Committee has indicated that so far he has received little support other than in the oceanographic group. Any who can aid in this matter will be doing a service to the membership as well as to AGU.

Statutes and By-Laws—The Committee on Statutes and By-Laws under the chairmanship of K. Hilding Beij has filed a report relative to the suggestions previously offered. (The By-Laws as they now stand appear in the *Transactions* of June 1955, pp. 564–568, and a copy of the suggested amendments appear as Appendix 3 of these minutes.)

International Geophysical Year—As noted above, N. C. Gerson has been designated Chairman of a new Committee on Relationship of AGU to the U. S. National Committee for IGY. Now actively under consideration and development is a plan whereby we will publish on a monthly preprint basis a news letter

for the U. S. National Committee relating to IGY of some 10 to 20 pages, these to be bound into the next subsequent issue of the *Transactions*. The acquisition of some 1500 or 2000 reprints should defray most if not all of the costs of this operation in order that they may be added pages to the *Transactions*. It is the thought that, in the *Transactions*, they will form a permanent chronicle of events and activities of the U. S. effort in this regard.

Education in geophysics—The AGU now has a student grade of membership which has been made readily available by the action of the Executive Committee based on the Landsberg report approved in November. Students may be signed up for student membership directly on the campus without formal action by the Executive Committee. This is a step to bring AGU to the younger workers in the geophysical sciences. Back in 1944 and 1945 the AGU made a survey of education in geophysics which was published in the December 1945 issue of the *Transactions*, with a supplement in the August 1946 number. The means for repeating this were not available, and the Society of Exploration Geophysicists subsequently took this up under the chairmanship of our late President, James B. Macelwane. Originally this pertained to exploration geophysics, but on suggestions from AGU the scope was expanded to cover geophysics in its broader phases. As there is a need for a survey of education in geophysics, we are making representation to the National Science Foundation for a grant for this purpose. It would seem that AGU might likewise have an opportunity for service in brochures and other material intended primarily for the orientation of high school students. A discussion of this is invited.

Directory of members—As directed by the Executive Committee at its last meeting, the AGU is exploring the possibilities of securing a grant from the National Science Foundation in order to publish its directory on an annual basis. The efforts so far have been rather discouraging.

NRC's Committee on Oceanography—At the request of the Fish and Wildlife Service, the Atomic Energy Commission, and the Office of Naval Research, the National Research Council appointed a Committee on Oceanography to offer advisory services to these Federal agencies in the field of oceanography. An *ad hoc* group met to discuss this matter under the auspices of the Division of Earth Sciences.

American Geological Institute—The American Geological Institute has requested us to take action with regard to the admission of the Geochemical Society to membership in the AGI. The original application was dated April 25, 1956, but for some reason this was not called to our attention until after the meeting of the Executive Committee in November. In the meantime favorable action has been taken by a sufficient number of affiliated organizations of AGI so that the Geochemical Society has been admitted. It is nonetheless recommended that we take formal action in this regard.

Miscellaneous—The Bureau of Labor Statistics has requested our aid in the preparation of a pamphlet on employment outlook for geophysicists. We have reviewed their drafts and made recommendations.

A number of invitations have come in for AGU participation in various functions including the inauguration of a new President of Franklin and Marshall College on April 6 and the inauguration of a new President of Ohio State University on April 29. The time schedule did not work out properly for designation of anyone to the inauguration at Franklin and Marshall, but C. V. Youngquist has been designated to represent AGU at the Ohio State function.

The National Education Association is holding a Centennial Convocation in Philadelphia in July and we are proposing to designate a representative.

Richard M. Field, Director of the American Institute of Geonomy and Natural Resources, had advised that the second award of the John Fleming Medal of his organization is to be made to W. Taylor Thom of Princeton University at Princeton University on the evening of May 2, 1957; Harry H. Hess will make the citation.

A. NELSON SAYRE,
General Secretary

Action on the General Secretary's report—The report was accepted.

Action on matters relating to the General Secretary's report—It was noted by Harry Hess, Chairman of the Division of Earth Sciences, that the NRC's Committee on Oceanography is not yet formed, that only a meeting of an *ad hoc* group was held, and that the Section of Oceanography is not properly equipped to take care of the matters to be dealt with since they bear on governmental operations and biological sciences as well as various phases of oceanography. It was moved and carried that we should indicate our willingness to aid and abet the work of the new Committee and express the expectation that a representative of AGU would be formally on the Committee.

The recommendation of the General Secretary relative to those who owe dues for 1955 to 1957 was accepted, namely, that a further attempt be made to bring these persons again into active membership. Those who do not respond appropriately will be dropped from membership.

There was considerable discussion of the need for a survey of education in geophysics. The mathematicians have just spent two years on a project surveying graduate-level education in mathematics, financed by the National Science Foundation. It was noted that if such a study is to be successful, it should be undertaken by a small committee of enthusiasts having its own full-time Executive Secretary and with an adequate budget. The President was authorized to appoint a committee to decide what should be done in this matter, and to recommend a program for the necessary financing.

After brief discussion, it was agreed that AGU should work out plans with the U. S. National Committee for IGY to print and include in the *Transactions* the contemplated substantive news reports of the U. S. National Committee provided that this does not decrease the material otherwise published in the *Transactions* and can be done without cost to AGU. This is to be preprinted in an edition of about 2000 for the U. S. National Committee.

The proposal to admit the Geochemical Society to membership in the American Geological Institute was approved.

Reports of Standing Committees

International Participation—Chairman Joyce reported on the Committee meeting held in Washington on the morning of April 28, 1957, as set forth in Appendix 1, which indicates the action taken by the Executive Committee.

Editorial and Publication—Chairman Sayre noted that most of the comments relating to the work of this Committee had been brought out in the General Secretary's report, but pointed out that the monograph project needs ways and means of financing and that we should give consideration to raising a revolving fund of $50,000 to $100,000 in order to meet the needs for monographs, possibly to take care of the monograph financial problem indefinitely.

Budget—Chairman Reed presented the budget report as set forth in Appendix 2 (circulated to the members of the Committee in advance). After a brief discussion, the budget was approved. Specifically approved was a motion that a savings account be opened in order that the Union's funds in excess of immediate needs might realize some additional income. The Budget Committee recommended the establishment of a Financial Advisory Committee to study problems of finance such as the advisability of investing some of the Union's funds now in building and loan associations in mutual associations in order to realize a higher return through appreciation. It was agreed that the Budget Committee should undertake these functions.

Statutes and By-Laws—Chairman Beij presented the report as set forth in Appendix 3 (circulated to members of the Committee in advance of the meeting). The report was accepted and motions approved relating to the five proposals for amendments to the Statutes and By-Laws.

Nominations—Chairman L. H. Adams noted that the Committee would get busy with its activity in time to be completed by the early fall of 1958 and that Section Nomination Committees should be organized in plenty of time to do likewise.

Meetings—Chairman Abelson raised the question whether our Annual Meeting should be held in a hotel instead of in the National Academy and nearby auditoria as under present arrangements. It was the consensus that the present arrangement worked out best for our purposes. He noted that there had been a meeting of the Pacific Southwest Regional Group (Vito A. Vanoni, Chairman) on February 14–15, 1957, and that tentative plans are under way for a meeting of the North Central Regional Group (Edward A. Brooks, Chairman), perhaps in St. Louis, which might join with the AAAS meeting to be held in Indianapolis in December. W. C. Krumbein, one of our two representatives on the Council of the AAAS, is exploring this matter with Chairman Brooks of the North Central Regional Group. The Pacific Northwest Regional Group (Norbert H. Leupold, Chairman, as of July 1, 1957) is planning a meeting to be held in late October 1957 at Pullman, Washington, and the Pacific Southwest Regional Group is planning another meeting for January or February 1958. The Mid-Pacific Regional Group (Geophysical Society of Hawaii; also affiliated with the American Meteorological Society) holds fairly regular meetings several times a year.

It was recommended and approved that our next Annual Meeting be held in Washington during the week following the meeting of the National Academy of Sciences. This makes our dates tentatively May 5–7, 1958.

Membership—Chairman Droessler presented the report set forth in Appendix 4, which was accepted. He also submitted a draft of a corporation membership brochure prepared by W. B. Foster, who is a member of his Committee and is also working on a new brochure for student members. He expressed the thought that it would be much more appropriate if the names of corporation members were printed in bold face type in a summarized list at the end instead of the ½ page now given to each corporation member, especially now that we accept advertising down to sizes as small as ¼ page. He noted that on November 29, 1946, the Executive Committee approved a three-part statement, item (3) of which read: "Corporation membership listing shall be on the basis of not more than eight entries per page, space for each entry to have full-page width. Each entry shall show the name, activity, and address of the member. The listing shall conform to the style of the *Transactions*." He moved and it was approved that this provision be deleted and that (1) and (2) preceding this item (3) be made to read: "(1) A list of corporation members shall be published on one or more pages immediately after the final page of text in each issue of the *Transactions*. (2) A list of corporation members shall be included in the Membership Directory as a distinct unit."

Reports of Special Committees

Relations with U. S. National Committee on IGY—Chairman Gerson reported that the Committee plans to hold its first meeting on May 2, 1957.

Advertising—Chairman Gerson reported that the Committee is being organized to help the advertising representative in the solicitation of advertising and in other ways. (The advertising representative, Mrs. W. A. James, sent word during the Annual Meeting that the doctor has advised her to give up some of her activity and that she would need to discontinue as our advertising representative after the completion of the work for the June issue. The Committee has undertaken an active campaign of solicitation of advertising for the August issue and will make recommendations for the future of this activity.)

Cosmic-Terrestrial Relationships—Chairman Vestine reported that the Committee is in the process of being organized, with Walter Orr Roberts as Vice Chairman. He noted that at least four members of the new Committee have suggested that a symposium on cosmic-terrestrial relationships be held in connection with the next Annual Meeting of AGU.

National Research Council Reports

Earth Sciences—Chairman Hess stated that he plans to prepare a written report for subsequent Executive Committee meetings, but gave no formal report at this time.

Unfinished and New Business

L. H. Adams moved and it was approved that a small and attractive brochure be prepared and distributed at the time of the Annual Meeting concerning the background and the current proceedings relative to the William Bowie Medal. P. H. Abelson thought it would be well to consider changing the time of the announcement of the recipient of the Medal. After extensive discussion it was agreed that the Committee would be guided by this discussion for action subsequently, and that it give serious consideration to plans for holding a subscription dinner for those who might want to come before the presentation.

It was moved and approved that the Executive Committee authorize the setting up of a President's Fund of $100 to be expended at his discretion and to extend this authority, at his discretion, to the General and Executive Secretaries to take care of possible official or semi-official expenses.

Recess—The Executive Committee went into a brief executive session and then recessed at 18h 15m, to be resumed immediately following the Business Meeting on May 1, 1957.

A. NELSON SAYRE, *General Secretary*
WALDO E. SMITH, *Executive Secretary*

Second Session, May 1, 1957

The second session was called to order at 16h 30m by President Maurice Ewing in the Auditorium of the National Academy of Sciences—National Research Council, 2101 Constitution Ave., N. W., Washington, D. C.

Present—Twenty persons were present as follows: P. H. Abelson, L. T. Aldrich, L. V. Berkner, Walter H. Bucher, J. J. Capello, S. D. Cornell, Frank L. Culley, Maurice Ewing, R. E. Gebhardt, Albert J Hoskinson, W. C. Jacobs, H. R Joesting, J. W. Joyce, Ray K. Linsley, James A. Peoples, Jr., John C. Reed, A. Nelson Sayre, J. Frank Schairer, Waldo E. Smith, and George P. Woollard.

Ray K. Linsley, President of the Section of Hydrology, noted that its Committee on Glaciers had assembled a rather extensive file of material on North American glaciers which is now on deposit with the American Geographical Society in New York and that the Society has been established as the World Data Center for Glaciology of the IGY and would like to integrate this material with the other material to be accumulated or already in hand. It was agreed that this should be done, with the understanding that the material would be adequately available to members of the Union in connection with our work on glaciers.

George P. Woollard, Chairman of the Special Committee on Geophysical and Geological Study of Continents, noted that data collected under the auspices of the Union and obtained from oil companies in cooperation with universities, the Geological Society of America, the U. S. Geological Survey, and the U. S. Coast and Geodetic Survey have now advanced to the point where this material may be brought together as a comprehensive gravity map of the United States. It seems as though it should be brought out with the new geologic and tectonic map being prepared by the U. S. Geological Survey and on the same basis, and he asked the concurrence of AGU on this plan. This was approved.

Adjournment—The meeting adjourned at 16h 35m.

A. NELSON SAYRE, *General Secretary*
WALDO E. SMITH, *Executive Secretary*

Appendix 1—Report of the Committee on International Participation

A meeting of the Committee was held in Washington on the morning of April 28, 1957 at which a detailed report of the meeting of the Interim Policy Committee of the IUGG which had been held in Paris April 10–12, 1957 was presented.

The following actions were taken by the Executive Committee at its meeting on April 28, 1957 based on a consideration of recommendations made in Paris by the Interim Policy Committee (IPC). (Asterisk indicates IPC recommendation.)

(1) *Adherence of new countries and territories*—The Executive Committee accepted the two recommendations made by the IPC as follows:

* RECOMMENDED AGREEMENT that the Policy regarding the adherence of new countries should aim at universality irrespective, if at all possible, of political difficulties, in order to ensure that the largest possible portion of the Earth's surface is adequately represented in the Union.

* RECOMMENDED AGREEMENT that tentative applications made to adhere to the Union cannot be adequately considered prior to the meetings of the Council and Executive Committee in Toronto, but that it would be helpful if the President be asked to send invitations for representatives from these countries to attend the General Assembly.

The Executive Committee accepted a third recommendation as follows:

RECOMMENDED that the AGU advocate the recognition of only one German Delegation at the General Assembly at Toronto, and that this be the delegation from the Bavarian Academy of Sciences which now adheres to the IUGG on behalf of the German Federal Republic (i.e., West Germany).

(2) *IUGG publications*—While the Executive Committee agrees with the concept of a modified *News Letter*, it recommends that the IUGG give full support to the proposed *ICSU Review* which will provide means for publishing news letter types of material from the ICSU and all of its Unions.

The proposal for an active high quality journal of geophysics to be undertaken by the Union was rejected on the grounds that there are already an adequate number of international journals on geophysics.

The Executive Committee adopted the following recommendations:

RECOMMENDED AGREEMENT that the *News Letter* be issued in a simpler and cheaper form, issued, say, eight to ten times a year, for free and wide distribution to member countries so as to give essential news but not general articles or reports. However, the IUGG should actively press for the establishment of the proposed *ICSU Review* and thenceforth discontinue the *IUGG News Letter*, distributing all newsworthy and other suitable items through the *ICSU Review*.

* RECOMMENDED AGREEMENT that the Associations be invited to consider the desirability of some measure of uniformity in publication as regards size, type of print, and, above all, value of contents. A uniform series of *Special Publications*, limited to special subjects, such as for Symposia, could be of high value to the IUGG. (This may involve the need for considering matters of editorship.)

The Executive Committee urged that the National Academy of Sciences—National Research Council undertake the assembly of as complete a collection as possible of Union and Association publications, and that this collection be maintained current.

(3) *Symposia*—The Executive Committee strongly endorsed the desirability of the IUGG initiating and sponsoring authoritative symposia of high scientific standards, with publication of the full text of papers and discussion on a commercial basis. The Executive Committee adopted the two recommendations made by the IPC and added seven additional as follows:

* RECOMMENDED AGREEMENT that the Associations be invited to consider, during their meetings at a General Assembly, the symposia which they would like to hold during the ensuing triennium, so that (a) proper financial arrangements can be made, (b) there will be clearing of dates, and (c) there may be participation by more than one Association if other Associations are interested.

* RECOMMENDED AGREEMENT that the Associations be also invited to consider the desirability of increasing the number of joint symposia during General Assemblies so that the Associations be more closely drawn into contact with one another and so to fulfill the basic idea of the Union.

RECOMMENDED the holding by the Associations of top-level scientific symposia, the papers and discussion from which will be suitable for publication as a commercial enterprise.

RECOMMENDED that each symposium be organized by a specifically chosen leader, an outstanding scientist, who will also act as editor in the preparation of the resulting volume.

RECOMMENDED that the Union (IUGG) be prepared to subsidize the expenses of invited specialists to symposia.

RECOMMENDED that papers must be prepared and be available in advance and that all significant discussion occurring during the symposia be included in the publication thereof.

RECOMMENDED that the geographic distribution of symposia take fully into account the world-wide responsibilities and character of the Union.

RECOMMENDED that, in those areas where formal symposia are not feasible, colloquia on appropriate subjects be held, with the idea of stimulating interest in the geodetic and geophysical sciences and in the affairs of the Union.

RECOMMENDED that Commissions should be ever alert to developments within the broad aspects of the field of the Association and take efforts to bring those new developments and active phases into the Association activity. Associations should also be alert to opportunity to initiate activity within the broad field of Association subject matter.

(4) *Joint commissions and special committees*—The Executive Committee adopted the IPC recommendation made at Paris as follows:

* RECOMMENDED AGREEMENT that the formation of Special Committees such as the Special Committee for Oceanographic Research (SCOR) as sponsored by the International Council of Scientific Unions is an excellent method of achieving valuable results in the subjects of common interest to Unions, especially if such Special Committees are given a very large measure of freedom to formulate scientific policies in conjunction with the participating Unions.

Berkner advised the Executive Committee that ICSU draws a distinction between a commission and a special committee. Commissions are now established primarily to arrange special symposia particularly on subjects which concern several disciplines. Special committees, on the other hand, are selected to carry through specific operational tasks such as, for example, the IGY. Under these circumstances, therefore, the IPC recommendation that commissions expand their functions beyond the arrangement of symposia was not accepted. The Executive Committee recommended that ICSU be asked to prepare rules for special committees in the same way that they have done for commissions.

(5) *Relations with other international organizations*—The Executive Committee approved the IPC recommendation as follows:

* RECOMMENDED AGREEMENT that the IUGG Council be invited to appoint representatives (a) to maintain liaison with other international organizations in which the IUGG is interested and (b) initiate working arrangements with these organizations.

(6) *Young scientists*—The Executive Committee concurred with the Policy Committee's attitude concerning the need to attract more young scientists to take an active part in all IUGG matters, and accepted the following IPC recommendations:

* RECOMMENDED AGREEMENT that every possibilty be explored by National Committees and by the Union so that young, active, and promising scientists are included among the delegates or guests at the General Assemblies. It is recognized that this may mean older scientists giving place to these younger men, and for financial assistance to be provided, either from a share of national funds or by direct assistance from other sources. Opportunities should also be provided for these younger men to take a share in the activities of the Union in its Committees and Commissions.

If an Association feels that it would be beneficial to their discussions at a forthcoming General Assembly and to the benefit of the future activities of the Associations if one or more younger scientists from a particular country could be present, they should feel at liberty to express to the appropriate National Com-

mittee their desire, and they should be prepared to use their Association Funds, so far as they are able, to give financial assistance.

It is also possible for the President of the IUGG, as stated in By-Law 5(c) of the IUGG, to invite, either on his own initiative or at the request of the President of an Association or at the request of a National Committee, individuals or guests of the IUGG. Under such circumstances there may possibly be financial assistance provided from IUGG funds, if no other sources are available. We recommend that advantage of this may possibly be taken with regard to younger men.

(7) *CSAGI*—The IPC recommendation concerning the union's responsibilities in connection with CSAGI was approved. This recommendation is as follows:

* RECOMMENDED AGREEMENT that the Union should consider as soon as possible how it may undertake the responsibilities which will undoubtedly devolve upon this and other Unions concerned after CSAGI has completed its present activities shortly after the end of the IGY.

(8) *Permanent Services*—The Executive Committee took no action on Interim Policy Committee recommendations concerning FAGGS, but it did recommend that the same individual should not act as the General Secretary of both the IUGG and FAGGS at the same time because of possible conflicts of interest.

(9A) *Interim Policy Committee*—The Executive Committee approved the following recommendation:

* RECOMMENDED AGREEMENT that the functions of a Policy Committee can best be performed by an enlarged Bureau of the Union, consisting of the President, the two Vice-Presidents, the General Secretary, the Chairman of the Finance Committee, and three members who are elected by the Council and who are specially chosen for their wide interests and knowledge of the Union's affairs.

(9B) *Rotation of the Presidency*—The Executive Committee noted with approbation the IPC opinion that the traditional rotation of the Presidency among all member countries is not in the best interests of the Union, and that in the future the best qualified persons should be elected to this important Union office.

(9C) *Names of Associations*—The need was recognized for establishing positions in connection with the two Associations whose names have been or will be the subject of changes, namely, the Association of Geomagnetism and Aeronomy and the Association of Volcanology. It was also recognized that eventually the Association of Seismology and Physics of the Earth's Interior and the Association of Volcanology might combine to form a single Association of the Earth's Interior.

J. WALLACE JOYCE, *Chairman*

Appendix 2—Report of the Committee on Budget for the Fiscal Year Ending June 30, 1958

JOHN C. REED, Chairman
E. H. BRAMHALL L. O. QUAM

Your Committee proposes the following Budget for the fiscal year ending June 30, 1958. The proposed Budget was prepared in consultation with the Executive Secretary and with the use of many data made available by him.

In the past, the American Geophysical Union has from time to time performed work for others, largely government agencies, under contract. Expenses relative to those contracts have been charged directly to the contract and fiscal data relative to the contracts have been excluded from the Budget. At the present time no such contracts are in effect although one may soon be signed. In a similar category, and not included in the proposed Budget, is a recent grant to the Union from the National Science Foundation in the amount of $22,400 for making certain translations. Also excluded from the Budget is the expected receipt of about $2500 from a recently concluded sale of excess copies of the *Transactions*. The item is not included because, at the time of preparation of the Budget, it is not known whether the money will be received in the present or in the next fiscal year.

Estimated receipts—The estimate of income from dues of members is based on the present membership. Your Committee feels that this is likely to be a somewhat smaller income from that source than will actually be received because of the energetic efforts that are being made to increase the membership. Receipts from advertising in the *Transactions* are estimated at the present level of advertising.

Your Committee notes that the bank balance of the Union ranges during a year from around $30,000 to as little as about $5,000. It is suggested that attention be given to the possibility of opening a savings account with the unneeded funds so that the Union may realize some additional interest income.

Also, the Committee suggests that the Union, either through an *ad hoc* Financial Advisory Committee or otherwise, may wish to inquire into the advisability of investing some of its funds that are now in building and loan associations in a mutual association in order to realize a higher return through appreciation.

The miscellaneous item of income represents largely postage returns, contributions, and the sale of unneeded equipment.

Estimated expenditures—Preparation of the *Transactions* includes some salary items and time in the office on proof-reading. The printing item was somewhat increased over the past year because of a cost increase of approximately ten per cent. The mailing estimate includes only direct mailing cost, not correspondence related to the *Transactions*. The editors are estimated on the basis of honoraria to nine editors at $150 each. Most of the $2500 estimated for direct advertising cost is compensation to one person at $200 per month. It is noted that the return from advertising is $6.000, but this may be in part offset by indirect increased printing and composition costs.

Most of the items under the heading of general office expenses are either fixed or are subject to rather

close estimation. The rental estimate is increased because the Union is now occupying an additional room. The item for postage and communications is largely postage, with only about $300 for telephone and telegraph.

The budget item for travel of officers has been increased from $150 a year ago to $1000. Your Committee believes that the Union should provide enough for one or more of its officers to attend at Union expense at least one appropriate meeting at a considerable distance from Washington.

The Directory reserve has been increased ten per cent because of the increased cost of printing.

The Budget presented by your Committee indicates an excess of expenditures over receipts of $700. This is not believed to be significant in view of the doubts in regard to some of the items involved. In any event, the resources of the Union are sufficient to absorb a small deficit, if it should occur. Your Committee believes that the financial status of the Union is satisfactory. The Committee believes that the apparent deficit could be offset, for example, by a modest increase in membership plus the investment of unneeded cash reserves in a savings account, as previously recommended.

Omitted from the Budget this year is the statement of assets as estimated for the beginning and end of the fiscal year. Previously this has been a customary part of the Budget report but your Committee feels it is the sort of statement that should be made by the Auditing Committee and not the Budget Committee.

The Committee wishes to express its appreciation of the help of the Executive Secretary in preparing this Budget and estimate.

Operating Statement

Estimated receipts:			
National Research Council grant		$400	
Income:			
Membership dues			
4884 members at $8	$39,000		
23 corporation members at $100	2,300		
Back dues (estimated) from 250 members at $8	2,000	43,300	
Transactions			
Sales and subscriptions	$12,000		
Reprints	4,000		
Advertising	6,000	22,000	
Interest			
Interstate Building Association	$300		
Northwestern Federal Savings and Loan Assn	400		
Liberty Building Association	40		
Prudential Building Association	80	820	
Miscellaneous		500	
Total receipts			$67,020
Estimated expenditures:			
Transactions			
Preparation	$7,900		
Printing	24,000		
Mailing	1,200		
Editors	1,350		
Direct advertising costs	2,500		
Cost of reprints	2,200	$39,150	
General office expenses			
Rent	$3,720		
Salaries and Social Security	17,000		
Retirement contribution	1,050		
Stationery and supplies	1,500		
Postage and communications	1,500		
Equipment	500	25,270	
Expenses for meetings			
Annual	$1,000		
Regional	100	1,100	

Expenses for Sections	100	
Expenses for Committees	100	
Travel of Officers	1,000	
Directory reserve	1,000	
Total expenditures		$67,720
Estimated excess of expenditures over receipts		$700

Appendix 3—Report of the Committee on Statutes and By-Laws to the Executive Committee

K. Hilding Beij, Chairman
W. B. Langbein C. A. Whitten

At the meeting of the Executive Committee on November 17, 1956, certain recommendations were made to the Committee on Statutes and By-Laws. (See *Trans.*, Feb. 1957, pp. 138–139.) The Committee has considered these recommendations and presents herewith proposals for amendments to the Statutes and to the By-Laws to bring the recommendations into effect.

(1) Amend the first paragraph of Article 4 of the Statutes to read:

> "*Article 4: Sections*—The American Geophysical Union shall consist of Sections as follows: (a) Geodesy; (b) Seismology; (c) Meteorology; (d) Geomagnetism and Aeronomy; (e) Oceanography; (f) Volcanology, Geochemistry, and Petrology; (g) Hydrology; (h) Tectonophysics."

This amendment changes the name of the Section of Terrestrial Magnetism and Electricity to agree with that of the corresponding International Association.

(2) Amend the By-Laws and Statutes as follows:

In By-Law (17) change the semicolon after the words "Special Committees" to a period and delete the words "in the absence or disability of the President, the Vice-President shall carry out the duties ordinarily performed by the President."

Change the numbers of present By-Laws (18), (19), and (20) to (19), (20), and (21) respectively.

Insert a new By-Law (18) to read: "(18) In the absence or in the event of the disability of the President, the Vice-President shall carry out the duties ordinarily performed by the President."

Amend the first paragraph of Article 5 of the Statutes by changing the words "in case any office becomes vacant" to "in case any office, except that of President, becomes vacant" and insert before the last sentence of the paragraph the new sentence "In the case of the death of the President, the Vice-President shall automatically become President."

These changes will insure that there will be no interval when the Union might be without a President, and formalize the duties of the Vice-President.

(3) Amend the second paragraph of By-Law (21) (present 20) to read as follows:

> "Each person and organization in good standing in any class of membership may purchase any available publication of the Union at a discount from the printed price-list to non-members. The General Secretary is authorized to establish discounts for sales of publications."

This change removes the present rigid restriction, and permits the General Secretary to set prices according to conditions prevailing.

(4) Amend the first paragraph of By-Law (21) (present 20) by deleting the words "July 1" and substituting therefor the words "February 15".

This change saves the Union from losses incurred by the sending of *Transactions* to those who do not later pay up their dues.

(5) Amend paragraph (d) of Article 3 of the Statutes as follows:

Insert the number "(1)" before the present paragraph, and add the new paragraph:

> "(2) Nationals of other countries having the same qualifications, elected by the Executive Committee of the American Geophysical Union; these may not vote or be officers of the Union or of its Sections, or delegates of the Union to International Assemblies or Meetings."

This change removes a restriction not applying to either the grade of "Member" or of "Student Member".

Appendix 4—Status Report of the AGU Membership Committee

At the November 17, 1956 meeting, the AGU Executive Committee endorsed the Landsberg *ad hoc* Committee report. This Committee was asked to examine into the question of how best the AGU Membership Committee might be organized to secure at least 1000 new regular members, 100 corporation members, and a continuous feed of student members.

Summing up very briefly, the Landsberg Committee noted the general expansion of geophysics in the U.S. and abroad and recommended that the AGU launch a vigorous membership campaign aimed at bringing into the Union the many prospective members now actively engaged in geophysics. The report recommended that new promotional brochures be prepared to give attractive up-to-date information on the Union to all prospective members. Further, it was recom-

mended that a new Membership Committee be organized with several sections to cover all facets of a membership campaign.

To date we have the following accomplishments to report:

(1) Early in January, with the personal help of President Ewing, the membership campaign was launched. The first order of business was the naming of chairmen to head the several sections of the new Membership Committee. In this we were very fortunate in attracting outstanding men of the AGU to work with us. I am pleased to report that assignments have been accepted for the following sections:

(a) University Members Section (covering students and teachers in geophysics): The chairman is Ben F. Howell, Jr., of Pennsylvania State University.

(b) Government Members Section: The chairman is Elliott B. Roberts of the Coast and Geodetic Survey.

(c) Industrial Members Section: This appointment is pending.

(d) Publicity and Brochures Section: The chairman is Willis B. Foster of the Office of Scientific Activities, Office of the Secretary of Defense.

(e) Membership Admissions Section: The chairman is W. E. Hiatt of the U. S. Weather Bureau.

(2) Howell has set about his job in a business-like way and has sent in specific suggestions for improving the application for membership form, particularly to meet the student membership group. As a result of this, a new AGU application form has been prepared and is now available for general distribution.

(3) Roberts has launched an extensive letter-writing campaign to a large number of government agencies, bringing to the attention of these many government employees the objectives of the AGU and stressing the importance of their application. In a follow-through effort, he is planning to appoint a keyman in each of the government agencies to act as a membership booster for the AGU.

(4) Foster has prepared a draft of a first-rate corporation membership brochure. The aim here is to attract a large number of corporation members to the AGU. Three copies of this are presented to the Executive Committee for consideration. Foster is now giving attention to preparing an appropriate brochure for regular and student members.

(5) Hiatt is organizing a membership admissions section which will thoroughly screen for the Executive Committee each membership application received.

The appointment of an Industrial Members Section chairman will be made shortly. One of his first tasks will be to assist in a wide distribution of the new corporation membership brochure.

At the next regular Executive Committee meeting I hope to be able to report on the numbers of new members coming into the AGU as the result of our membership campaign.

EARL G. DROESSLER, *Chairman*

Special Announcements

NOTICE OF INTENT TO CHANGE THE BY-LAWS—Article 13(b) of the Statutes provides for changes of the By-Laws by action of the Executive Committee on recommendations of the Committee on Statutes and By-Laws, with the proposed amendments to be published in the *Transactions* not less than 30 days prior to a meeting of the Executive Committee at which confirming action is to be taken. Notice is hereby given that the changes in the By-Laws set forth in Appendix 3 of the minutes of the Executive Committee meeting published on page 608 of this issue of the *Transactions* will presumably be acted upon by the Executive Committee at its meeting in the autumn. Please note that this applies only to changes in the By-Laws; changes in the Statutes require action by the membership, and items for change of the Statutes in Appendix 3 shall be submitted to the membership for formal ballot in due course.

MEETING OF PACIFIC NORTHWEST REGIONAL GROUP—The Pacific Northwest Regional Meeting will be held at Washington State College in Pullman, Washington, October 30–31, 1957, to meet at the same time as the hydraulics conference scheduled for that site October 28–30. Interested persons should get into touch with Franklin I. Badgley, Secretary of the Pacific Northwest Regional Committee (Department of Meteorology, University of Washington, Seattle 5, Wash.) or with Norbert Leupold (P. O. Box 5082, Portland 13, Ore.) who, on July 1, 1957, became the Chairman of the Regional Committee replacing Clifford A. Barnes.

MEETING WITH THE AAAS IN INDIANAPOLIS—It is the plan that the AGU will join in the AAAS meeting, December 26–31, 1957. Program arrangements are in the hands of Edward M. Brooks, 3621 Olive Street, St. Louis, Missouri. Interested persons should get into touch with him.

PACIFIC SOUTHWEST REGIONAL MEETING IN PASADENA, FEBRUARY 6–7, 1958—The Pacific Southwest Regional Meeting will be held at California Institute of Technology in Pasadena, February 6–7, 1958. The Program Chairman is Eugene N. Bollay of North American Instruments, Inc., 2420 North Lake Avenue, Altadena, California, with Townsend Cromwell, Sr., of Scripps Institution of Oceanography at La Jolla and Norman H. Brooks of the Department of Civil Engineering at California Institute of Technology as members. Interested persons should write to one of them or to the Regional Chairman, Vito A. Vanoni, California Institute of Technology, Pasadena.

THIRTH-NINTH ANNUAL MEETING—The Thirty-Ninth Annual Meeting of AGU will be held in Washington, D. C., May 5–7, 1958, Monday through Wednesday. This is a first call for titles and abstracts of papers and for suggestions of symposia and other matters relating to the meeting. Send communications to P. H. Abelson, Chairman of the Committee on Meetings, 2801 Upton Street, N. W., Washington 8, D. C.; to the office of AGU, 1515 Massachusetts Avenue, N. W., Washington 5, D. C., or to the appropriate Section Secretaries.

NATIONAL ACADEMY OF SCIENCES

Number 1 • July 1957

IGY BULLETIN

A monthly survey by the U. S. National Committee for the International Geophysical Year. Established by and part of the National Academy of Sciences, the Committee is responsible for the U. S. International Geophysical Year program in which several hundred American scientists are participating and many public and private institutions are cooperating.

THE purpose of the Bulletin is to present current information on the IGY program of interest to scientists and particularly to geophysicists. It is hoped that the Bulletin will be of value to participants in the program by keeping them informed of progress in our own program and in the programs of other countries.

The contents of the Bulletin will include brief articles and reports on projects and experiments in the U. S. program as well as scientific news of activities in other countries, obtained from the Comité Spécial de l'Année Géophysique Internationale (CSAGI).

The Bulletin will attempt to present information in each of the disciplines of the IGY program and in such areas as the Antarctic where regional features are important. The first few issues will provide background for more specific later reports.

The Bulletin can not be comprehensive. The scope of the IGY program precludes this, for the endeavor embraces the efforts of thousands of scientists in the United States and in some sixty nations abroad.

The program in the United States has been developed by American scientists themselves under the auspices of the National Academy of Sciences. To plan and direct the U. S. effort, the Academy established the U. S. National Committee for the International Geophysical Year. The Committee, with its regional committees and specialized technical panels, has cooperated with similar committees of other countries in developing the coordinated, international program and is responsible for the U. S. contribution.

In the development of the U. S. program the National Academy of Sciences has had the cooperation and assistance of hundreds of scientists and many public and private institutions. In any listing of the public institutions assisting in the program perhaps two agencies stand out: the National Science Foundation and the Department of Defense. The Committee has secured Congressional appropriations totalling $39 millions through the National Science Foundation for the specially funded portions of the IGY program, and the Foundation has assisted the Committee in many areas involving the Government. The Department of Defense, aside from contributions of scientists in its laboratories, has provided major logistics support. The Antarctic and the Arctic are examples where appreciable field assistance, involving ships and aircraft, has been provided, while the rocket vehicle aspects of the IGY satellite program afford still another example.

In the course of reporting IGY progress, the Bulletin will relate experiments to institutions and scientists. The contents of articles will be drawn from progress reports submitted to the Academy, correspondence, and discussions. The assistance of participating scientists and institutions is necessary for the preparation of the Bulletin.

—Hugh Odishaw, Executive Director, U. S. National Committee for the International Geophysical Year, National Academy of Sciences.

Antarctic Program

On May 11, 1957 while the Little America IGY Station at Kainan Bay in Antarctica experienced +30°F temperatures, the Amundsen-Scott IGY South Pole Station recorded a world low of −100°F. The unseasonably warm temperatures at Little America caused roofs to leak while heavy wet snow covered up buildings and caches. At the same time, personnel at the South Pole experienced the severest temperatures under which man has ever lived. Despite these conditions, efforts over many months to install USNC-IGY scientific programs at six U. S. Antarctic stations have met with complete success. Scientific observations designed to contribute to the overall International Geophysical Year program will be in full operation prior to the commencement of the Year on July 1, 1957.

Preliminary Operations and Planning

Completion of current test observations at these USNC-IGY Antarctic scientific stations is a major step forward from the voyage of the USS Atka in 1954–55, the first operational aspect of this program. The United States Navy, which had been designated by the Department of Defense to provide logistic support to the USNC-IGY program, sent the USS Atka to Antarctica in the fall of 1954 for a reconnaissance mission to the Ross Sea area, where it discovered that a substantial portion of the Bay of Whales, location of four previous Little America sites, had vanished with the break-off of a huge section of the shelf ice. Kainan Bay, some 30 miles to the east, was discovered to provide the only access to the Ross Ice Shelf in this area and the main USNC-IGY station was recently constructed here. The Atka also attempted to penetrate the ice barrier at several other points on her voyage eastward to the Weddell Sea area, carrying out a reconnaissance of other possible station sites. Some ice studies and oceanographic studies were made, providing data useful for further planning for the USNC-IGY Antarctic program.

With the information made available by the Atka's voyage, as well as by previous Antarctic expeditions, the USNC-IGY formulated final plans for its IGY Antarctic program at the first and second CSAGI Antarctic Conferences held at Paris and Brussels during the summer and fall of 1955. Representatives of eleven national committees coordinated their Antarctic programs at these Conferences, discussing not only the scientific programs to be carried out by each participating nation, but also such matters as the distribution of Antarctic stations and the proposed Antarctic communications network.

Among the resolutions resulting from these conferences was one designating the United States to establish a meteorological center during 1957–59, collecting information from all Antarctic stations, traverse parties, air and surface craft, ocean islands, and stations in South America, Africa, Australia, and New Zealand. This IGY Weather Central, which has since been established at Little America Station, will serve as an analysis center and, for the first time in history, daily weather maps will be prepared for Antarctica. Weather advisories and forecasts important to the planning and execution of operations on land, sea, and in the air will be issued regularly.

1955–56 Operations

During November 1955, ships of Naval Task Force 43 departed from the U. S. to conduct Operation Deep Freeze I. Three icebreakers, three cargo vessels, an oil tanker, and two oil barges proceeded to New Zealand and left there in December to take up picket positions along a flight line to McMurdo Sound. Four long-range planes successfully landed on the ice of McMurdo Sound. The ships of the Task Force then

proceeded to set up two stations on the Ross Sea.

Little America Station was established at Kainan Bay, about 40 miles east along the edge of the Ross Ice Shelf from the site of the former Little America Station, and 70 personnel wintered over during 1955–56 in anticipation of the early seasonal traverse operation needed to establish the Byrd Station in Marie Byrd Land and to finish station construction. Williams Air Operations Facility, at Hut Point on Ross Island in McMurdo Sound, was constructed as a support base for the future airlift to the South Pole, and 93 personnel remained during the winter season.

While construction of stations and unloading of cargo ships were in progress, preliminary work for the operations of the 1956–57 Antarctic summer was begun. A party of light oversnow vehicles reconnoitered a trail from Little America toward the site of the proposed Byrd Station in Marie Byrd Land. The trail reconnaissance party marked 380 miles of their 600 mile route before turning back because of mechanical trouble with their vehicles. Two cache-laying sled swings laid out fuel depots on the trail for use during the establishment of the station which was to commence in October, 1957.

Before returning to New Zealand in mid-January, 1956, the four long-range aircraft based at McMurdo Sound completed reconnaissance flights over the polar plateau following the course to be utilized by aircraft in establishing the Pole Station in the operating season of 1956–57.

Additional activities conducted during Operation Deep Freeze I included a survey of the east coast of Victoria Land for a site for the establishment of a joint New Zealand-U. S. station. One of the icebreakers cruised along the Knox Coast in East Antarctica and the Filchner Ice Shelf on the Weddell Sea to reconnoitre locations for two additional stations. IGY representatives accompanied these reconnaissance cruises, as well as overseeing the unloading and caching of IGY supplies at the present station sites.

Among the materiel transported to the Antarctic by Task Force 43 was equipment to set up and operate the Byrd and Pole Stations. Cached both at Little America and McMurdo Sound, this cargo was to be carried to the station sites early in the 1956–57 operating season.

Scientific Activities—As the objective of Deep Freeze I was the establishment of the two stations in preparation for the IGY, only limited scientific projects were scheduled. However, some observations in cosmic rays, meteorology, oceanography, and atmospheric noise were carried out.

One of the ships was equipped with a cosmic radiation observatory, which operated continuously throughout the expedition. The neutron monitor employed in this observatory threw new light on the position of the magnetic equator, upsetting earlier conceptions of its location.

There was a meteorological observer aboard each ship of the Task Force, and one IGY representative versed in Southern Hemisphere meteorology was present as a consultant. The observers performed standard surface observations of temperature, pressure, winds, clouds, and other phenomena. Several of the ships made upper air soundings and winds aloft observations using balloons, radiosonde transmitters, and radar tracking devices. Special plastic balloons in limited numbers were released for the study of high altitude constant level winds. Other balloon flights of unusual nature were those carrying black bodies for radiation investigations.

A special meteorological unit operated as a weather central throughout the duration of the expedition, receiving reports from all the ships of the Task Force, as well as from land stations and other ships, both in the Antarctic and to the north. This unit drew daily weather maps and issued forecasts for the benefit of parties moving and working in the area.

The concentration of ships in such num-

bers in the Antarctic region permitted oceanographic observations during the course of operations. Continuous echo soundings of the ocean bed were made south from Panama. Bathythermograph observations were made in the Pacific and during passage across the Antarctic Convergence, through the Peru Current, and in the area from the Ross Sea to the Bellingshausen Sea. Other observations included bottom sampling, water and temperature samplings to depth, transparency readings, and color determinations.

A schedule of astronomic positions was set up. At each of these positions, gravity and geomagnetic observations comprised part of the program. At each port of call on the cruise to and from the Antarctic, gravity readings were taken. Other scientific projects conducted during Operation Deep Freeze I included investigation of VLF and LF radio wave propagation and studies of atmospheric noise.

During the winter, IGY representatives at Little America and McMurdo Sound monitored the scientific supplies and conducted geophysical observations. They carried out meteorological studies and tested observational equipment. They also made auroral and meteor studies, perfecting techniques for observing and recording data in advance of full-scale IGY programs. Radar meteor recording apparatus received operational testing.

1956–57 Operations

To coordinate the final effort for the establishment of Antarctic stations, a third international CSAGI conference on the Antarctic was held in Paris during July-August 1956. As during the two previous CSAGI Antarctic conferences, plans for the scientific programs and logistics operations were exchanged and discussed, including the

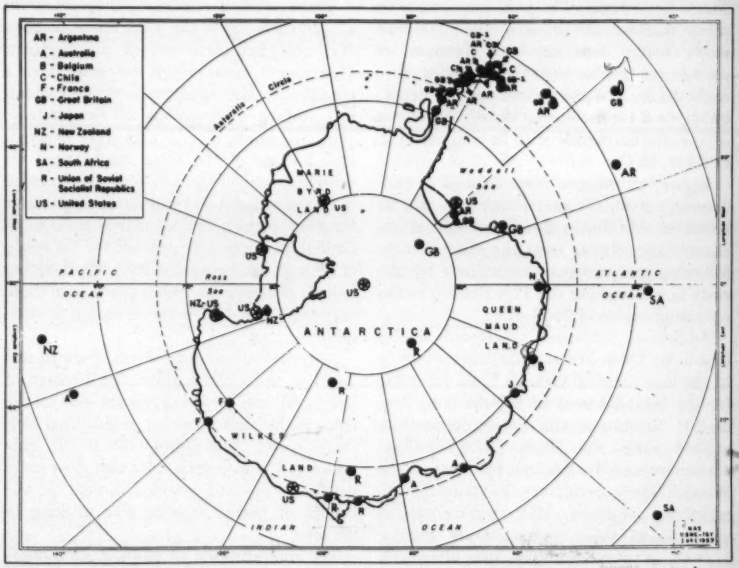

Fig. 1. *Antarctic Stations Planned For The International Geophysical Year*

coordination of the international communication network essential for linking all Antarctic stations and for the operation of the Weather Central.

Although the 1956–57 Antarctic operation formally began with the departure of the icebreakers and cargo ships in late October and early November 1956, activity preceding these events included the processing of 420,000 pounds of scientific equipment and supplies at Davisville, Rhode Island. An orientation program was held during October 1956 for USNC-IGY Antarctic scientific personnel at the Navy Construction Battalion Center, Davisville, Rhode Island. Scientific leaders for the six stations were appointed as follows: A. P. Crary (also Deputy Chief Scientist), Little America Station; G. R. Toney, Byrd Station; P. A. Siple, South Pole Station; C. R. Eklund, Wilkes Station; Finn Ronne, Ellsworth Station; and J. A. Shear for the Adare Station, operated jointly with New Zealand.

Establishment of the South Pole Station—Antarctic operations for the IGY Amundsen-Scott South Pole Station began during October 1956 when Naval and Air Force aircraft landed on the bay ice in McMurdo Sound after a 2200-mile flight from New Zealand. Preliminary reconnaissance flights over the South Pole and Beardmore, Scott and Liv Glaciers resulted in the establishment of an Auxiliary Air Facility at the foot of the Liv Glacier on October 29. Two days later, in −58°F temperature, a ski-equipped Navy airplane with Rear Admiral George Dufek, Commander of supporting Task Force 43, aboard, made the first historic landing at the South Pole. Weather conditions prevented further operations until November 20 when the first airlift of construction personnel and equipment was made. By February 21, 760 gross tons had been dropped during a total of 65 missions. At present 18 men (9 scientific and 9 support personnel) occupy the station. All personnel have been engaged in the completion of the station facilities in temperatures which have already dropped as low as −100°F.

In the installation of scientific equipment for studies of aurora, glaciology, geomagnetism, ionospheric physics, meteorology and seismology, some of the usual problems associated with scientific efforts in the field have been encountered, as well as some unique to this location. The extreme temperatures have caused constant frosting of aurora and airglow domes, which has had to be corrected by experimentation at the station site. Airdrop damage of the ionospheric equipment necessitated the rewiring of several circuits. Lost items have had to be replaced by equipment improvised at the station. In spite of these problems, all disciplines have now installed their equipment and are currently operating on a trial basis.

Establishment of Byrd Station—While great attention was focused on the Pole Station operation, a dramatic attempt was being made to establish a station in the interior of Marie Byrd Land. On November 9 a reconnaissance trial party composed of an experienced Army team supported by Naval aircraft equipped with oversnow vehicles departed from Little America. About 100 miles out on the trail, almost impassable crevasses were encountered which for some time threatened to jeopardize the success of the whole operation. After considerable reconnoitering, and days of patiently bridging crevasses, however, this region was crossed. After five weeks of intensive and hazardous work along the 650-mile route, the train arrived at the site of the Byrd IGY Station. Two heavy tractor trains, along with delivery of 240 tons of fuel and equipment in February by the U. S. Air Force, brought the supplies, scientific equipment and personnel needed to establish the station.

The late construction schedule, the constant wind-blown snow and low temperatures, made the completion of Byrd IGY Station a difficult task, but the 12 scientific and 10 support personnel have successfully completed the erection of buildings and special scientific structures. The meteoro-

logical program is already underway and the aurora, geomagnetic, ionospheric and seismic instruments have been installed, operating on a test basis.

Completion of a 650-mile glaciology-seismology traverse from Little America to the Byrd Station represented a significant achievement, operationally and scientifically. A seismic profile, begun 200 miles out from Little America, has shown that the ice depths increase from 2000 to 7000 feet approaching the station. A profile in the immediate vicinity of the site has determined that this station, which is only 5000 feet above sea level, is located upon 10,000 feet of ice: these data must be regarded as tentative pending more detailed studies.

A route for the 1957–58 IGY glaciological traverse planned at this station has been indicated as follows: Byrd Station to 76°S, 110°W to 77°30′S, 85°W to Byrd Station. The tentative route for the 1958–59 operation will be Byrd Station to 84°S, 110°W to 81°S, 75°W to Byrd Station.

Occupation of IGY Little America Station—With the arrival of the USS Curtiss at Kainan Bay on January 29, 25 IGY scientific personnel occupied the Little America Station. Included among these were Soviet and Argentine meteorologists, who will participate in the work of the Weather Central program. The IGY meteorological program was the first to get under way at Little America with surface and upper air observations beginning January 29.

Special programs are also currently under way. Installation and preparation of the aurora, geomagnetism, glaciological and ionospheric physics equipment are now completed, and data are being obtained. A week's seismic-gravity traverse on the Ross Ice Shelf along the route to Byrd Station has been completed and oceanographic studies of the Ross Sea at the Barrier's edge are being completed. Pit studies have been made at the site of the former deep pit at Little America No. 3.

The IGY Weather Central established at Little America Station, which is to serve as a clearing house for Antarctic weather information, has begun operations. Weather data are being collected on a regular schedule from all Antarctic stations and from nearby ships and aircraft, and from over-land traverse parties. For the first time, a coordinated forecast study of weather data from the far southern latitudes will be available to all nations.

Analyses of recently received data at the Weather Central include surface maps drawn four times daily at 700, 500, and 300 mb., once daily for regions where these data are available. Adiabatic charts have also been completed for these same stations. Preparation of hourly surface charts at 0000, 0600, 1200, and 1800 hours are being completed for stations from which data have been received. It is estimated that full weather collection and broadcasting will commence by June 1 and that analyses broadcasting should begin June 1 if sufficient data are available.

The IGY glaciological traverse party which will operate out of Little America plans to cover the following route during the 1957–58 operation: from Little America to the edge of the Ross Ice Shelf, thence southeast to the Liv Glacier and north to Little America. The proposed route for the 1958–59 traverse is as follows: The party will depart from Little America Station and proceed via the Byrd Station trail to 80°S, 140°W, a point just beyond the heavily crevassed barrier edge. The route will then continue to 77°S, 130°W, to 80°S, 125°W to 83°W, 130°W to 80°S, 140°W and back to Little America Station.

Establishment of Ellsworth Station—A reconnaissance of the Filchner Ice Shelf from Gould Bay to Cape Adams in January 1957, during which ships of the Weddell Sea task group constantly battled heavy pack ice, disclosed no satisfactory station site on which to establish the Ellsworth IGY Station. After exploring the barrier edge which ranged between 150 and 200 feet in height, unbroken for some 200 miles, a site east of Gould Bay was selected for the station and

on January 25 off-loading of cargo began. Off-loading and preliminary construction were completed in the record time of 14 days and the ships departed on February 12. A total of 39 personnel (14 scientific personnel, 14 support personnel and 11 Naval air personnel) have since been engaged in the installation of all scientific equipment for aurora, ionospheric physics and meteorology. Despite the extremely short construction period, installation of all scientific equipment was completed on April 15. Seismic and gravity equipment has been installed in an over-snow vehicle.

In preparation for next year's glaciological-seismic traverse on the Filchner Ice Shelf, the Ellsworth Station Glaciological Traverse for 1957–58 will plan to proceed along the following route: Ellsworth Station to 82° 30′S, 60°W to 78°S 60°W and back to the station. For 1958–59 the route will be Ellsworth Station to 82° 30′S, 20°W to 77° 30′S, 20°W to the station.

Establishment of Wilkes Station—After a reconnaissance of Vincennes Bay, a site on Clark Island was selected on January 29 for the Wilkes IGY station. Off-loading was completed by an amphibious operation and the ships departed on February 17. While 13 support personnel complete the station facilities, the 14 scientific personnel are finishing installation of scientific equipment. The selection of this site is most fortunate; there is an unlimited horizon for aurora observations, and the presence of bedrock makes the location an excellent one for the seismic program. The aurora, meteorology (including two daily balloon flights) and ionospheric physics programs are in full operation and the geomagnetism and cosmic ray programs await only the final preparation of special facilities before recording will begin.

The glaciological team has already established a route to the ice cap and has proceeded to a point 50 miles inland at an altitude of 4000 feet. Ablation and accumulation stakes were set along the trail and snow studies made.

A satellite station was established at a point 50 miles south of the station; here glaciological and meteorological observations are being carried out. This station has been occupied several times within recent weeks. A small glaciological station has also been established on the ramp to the ice cap, at which glaciological movement studies are being carried out. The aurora, ionospheric physics and meteorological upper air programs are currently beginning operations.

Establishment of Adare Station—Cargo for the joint New Zealand-United States Adare Station at Cape Hallett was off-loaded on January 10. By January 29 all buildings had been completed. The 8 scientific and technical personnel, including 3 New Zealand scientists, and 5 support personnel, have been installing the scientific equipment. Three-hourly surface meteorological observations were begun on January 10, 1957, and twice-daily upper air observations began April 1. Observations in the auroral, geomagnetic, seismic and ionospheric physics programs were expected to begin by June 1.

Arctic Drift Ice Station Program

Two drifting stations in the Arctic ice pack have now been established to study oceanography, meteorology, aurora, gravity, ionospheric physics, and ice physics.

Station A is located at approximately 80°N, 159°W, on a section of sea-ice which averages about seven feet in thickness and is about two miles in both width and length. Station B (Fletcher's Ice Island), composed of shelf ice, is about ten miles long, up to

four miles wide, and 140–160 feet thick. It is drifting in the area of 82° 46′N, 99° 30′W, about 510 miles from Thule Air Force Base.

Operational Aspects

Operations for the location and occupation of the two ice stations were conducted by air. The United States Air Force carried on the reconnaissance, constructed the landing facilities, and ferried in both equipment and personnel. Col. Joseph O. Fletcher, Arctic Basin Project Leader for the USNC-IGY, assisted in the reconnaissance for Station A.

The selection and establishment of suitable surface conditions were met with difficulties which attend polar basin activities. Reconnaissance for Station A began early in March 1957, and the first landing on the site finally selected came April 12. Ice conditions in the unusually warm winter required selection of a location somewhat further north than had been anticipated. On April 23, equipment was air-dropped for clearance of a 5000-foot runway, 200 feet wide. Ice hummocks slowed the work considerably, but by May 3—after additional equipment was dropped—an area 3500 feet long, 150 feet wide, had been cleared.

The first landing at Fletcher's Ice Island was made March 7. Construction of a 5000-foot runway began April 5 and was virtually completed April 23. Radio communications during the runway construction period were infrequent due to intermittent blackout conditions. Temperatures at this time dropped to −65°F, causing considerable difficulty with hydraulic lines in construction equipment.

The major airlift to Station A was scheduled for the period May 20–25, 1957. All scientific equipment and personnel were to be ferried to the island at that time. On May 23, a further report stated that the landing field had been completed and flag-raising ceremonies held. The normal complement, including nine scientists, will be about 20 persons. The IGY Station Scientific Leader is Maurice Davidson, of the Lamont Geological Observatory, Columbia University.

Nearly half of two years' supplies for Station B were to be on hand by mid-May. The normal complement there will be approximately the same as at Station A. IGY Station Scientific Leader has been Norman Goldstein, Geophysics Research Directorate, AFCRC.

Scientific Objectives

The contribution of the drifting stations to the overall USNC-IGY glaciology program in the Arctic involves measurement of the annual mass budget of the Arctic sea ice and its relation to total accumulation and ablation at the ice-ocean and ice-atmosphere interfaces respectively. A determination will be made of the annual thermal regimen of the Arctic sea ice and its relation to the net energy exchange across the interfaces. Also there will be determined the respective roles of short- and long-wave radiation; the thermal energy of accumulation, condensation, sublimation, and evaporation; the molecular conduction of heat; and the turbulent transfer of heat in the energy exchange across the interfaces.

Accumulation and ablation of the upper surface of the ice pack will be measured by the combined use of stakes to determine the rise or fall relative to a fixed reference plane within the ice floe, together with measurements of weight differences over given time periods, of vertical cores through the surface snow and ice. Actual procedures must be developed by trial methods at the stations.

Accretion or ablation of ice at the bottom of the ice pack will be determined from a series of cores taken through the ice pack every two or three months.

In other disciplines, aurora will be photographed at both stations by all-sky cameras, and, at Station A, a patrol spectrograph will be used and airglow spectra taken; geomagnetic data will be acquired through use of an Askania Variograph at Station A; incoming and reflected solar radiation will be measured. A vertical incidence sounder will

be utilized at Station B in the ionospheric physics program and at Station A, upper air studies will be made, using balloons. Gravimeter observations will be made at both stations.

Oceanographic data will be gathered on current flow, temperature and salinity at different depths; age determinations will be made on water samples taken from various depths; bottom cores will be taken to permit comparison of Arctic Ocean sedimentation, stratigraphy and marine life with that in other oceans.

Windspeed data will be gathered at six levels, temperatures measured vertically, and surface synoptics prepared. It is also planned to position two automatically recording weather buoys between Station A and Point Barrow. These will gather data on wind direction and speed, air temperature and barometric pressure. They will also be employed in monitoring the movement of ice.

The Earth Satellite Program

The USNC-IGY earth satellite program is designed to provide an observatory in the upper atmosphere over a wide range of latitudes and for an extended period of time. Besides functioning as an observatory by virtue of its instrumentation, the satellite itself may be observed from the ground for several additional scientific purposes.

Satellite Rocketry and Launching

The satellite will be launched from Patrick Air Force Base at Cape Canaveral, Florida, in an easterly direction so as to take advantage of the earth's rotation to gain added velocity. A 72-foot, three-stage rocket will be used; it will be finless, using internal controls for guidance. The vehicle design, construction, and launching aspects of the program are responsibilities of the Naval Research Laboratory and its contractors; prime contractor is the Martin Company of Baltimore.

The first stage will have a thrust of 27,000 lb and will propel the system upwards, tilting gradually until at burnout the vehicle will be at an inclination of approximately 35°. The first stage will be discarded at burnout and the second stage will take over.

The second stage will contain the guidance system for the flight control of all three stages: guidance during the active flight of the first two stages, guidance during the coasting of the second stage, and guidance for the initiation of the third stage.

The second stage motor, gimbal mounted like the first, will drive the vehicle to an altitude of about 140 miles and then coast some 700 miles to attain the desired altitude of between 250 and 300 miles. At this altitude, after the nose cone has been ejected, a pinwheel array of jets will spin the vehicle. The third stage will then quickly consume its solid fuel in impelling the satellite into its orbit at the necessary orbital velocity of 18,000 miles per hour.

Physical Description and Orbit

The first satellite will be spherical, about 20 inches in diameter, and will weigh approximately 21.5 pounds. About a quarter of this weight will be required for the satellite shell and internal structure; the remainder will be left for the various instruments, including the telemetering system.

The satellite's orbit will permit it to revolve about the earth in an apparent latitude range of about 35° on either side of the equator. The satellite will have an elliptical orbit with perigee about 200–300 miles and apogee 800–1500 miles above the earth.

Orbit Computation

Radio tracking and teams of visual observers will gather preliminary data on the satellite's location in space. These data, gained during the early revolutions of the satellite, will be fed into high-speed electronic computers. The results will establish an approximate satellite orbit, permitting observers throughout the world to train their instruments on the satellite, and also permitting precision Schmidt cameras to make photographic measurements of the satellite's position.

The second step, which involves both the radio and photographic observation stations, will be to process the extensive subsequent data in order to compute the orbit accurately.

The third phase of these programs involves the analysis of the precise orbit data. Such analysis will yield important scientific information in a number of areas.

Radio Observations and Measurements

Radio observations will employ a system developed by the Naval Research Laboratory. It is a precision, several-component system known as Minitrack. The expected precision of observations is about three minutes of arc under normal conditions with improvement to a precision of 20 seconds of arc for observations at small zenith angles and for night operation.

The Minitrack system makes use of established radio interferometric principles. It utilizes a transmitter of minimum size and weight within the satellite to illuminate pairs of receiving antennas at ground stations. By comparing the path length from the transmitter to one antenna with the path length from the transmitter to a second antenna, it is possible to locate the satellite in its orbit, determining its angular position by radio phase-comparison methods. Similar measurements with another set of antennas, at right angles to the first set, help to fix the satellite accurately.

The pattern of the Minitrack antennas will be fan shaped. At satellite heights, the beam will be several hundred miles wide. In this way a chain of stations stretching from latitude 35° north and south could intercept the satellite at each passage. Station sites have been located at or near Washington, D. C.; Savannah, Georgia; Havana, Cuba; Antigua, British West Indies; Quito, Ecuador; Lima, Peru; Antofagasta, Chile; Santiago, Chile; San Diego, California; and Woomera, Australia.

Optical Observations and Measurements

Optical observations of the satellite will be effected by several programs. The most precise optical observations will be made using a modified Schmidt camera developed for the optical tracking program of the Smithsonian Astrophysical Observatory. Continuous strip film will simplify the problem associated with following the satellite. To provide accurate timing, crystal clocks calibrated against WWV will give a signal for photography simultaneously with the satellite. Time must be read to the millisecond.

A modified Schmidt camera of much better optical quality and field than the standard Schmidt camera has been designed by James G. Baker. Strip film of approximately 55 mm width will be used to eliminate the need for film molding on the spherical focal surface and to permit rapid change of film so that short exposures may be made in twilight where the sky brightness may approximate that typical during full moon conditions. The field covered will be about 5° x 30°.

Optical tracking stations are planned in New Mexico, U. S. A.; Florida, U. S. A; Olifantsfontein, South Africa; Haleakala, Maui, Territory of Hawaii; Tokyo, Japan; Curacao, Netherlands Antilles; Cadiz, Spain; Shiraz, Iran; Arequipa, Peru; India; Villa Dolores, Argentina; Woomera, Australia.

The Schmidt camera system requires that the path of the satellite be known initially to a precision of about three degrees so that

preliminary sighting positions can be established. The radio tracking system will give this information, but in the unlikely event of radio failure in the satellite a network of organized volunteer observers will provide protection.

Although a particular individual will obviously have difficulty in viewing the satellite, trained teams of observers can undertake a satellite acquisition program.

Ground Station Experiments

An important area of scientific inquiry during the earth satellite program can be explored by means of careful analysis of orbital data acquired by ground stations, both radio and optical stations. The following are four areas of study that may be conducted:

(1) *Air density*—Very little is presently known about the density of the upper atmosphere. From the geometry of the satellite's course and observations of its flight, calculations can be made of air drag.

(2) *Geodetic determinations*—Observations of the satellite's orbit should furnish valuable data on the oblateness of the earth. In addition, improvements in the map of the world may be derived from simultaneous as well as synchronized fixes upon the satellite if its orbit is determined accurately enough. These observations would supplement the measurements planned in the IGY latitude and longitude program.

(3) *Ionospheric measurements*—The radio signal from the satellite will be refracted on passing through the ionosphere. The more oblique the passage, the more pronounced will be the refraction and the resultant displacement of the altitude of the satellite as indicated by this radio observation. Comparison of this apparent altitude with that derived from the computed orbit, based on many observations, will indicate the amount of ionospheric refraction and permit calculation of some of the electrical charge characteristics of the ionosphere.

(4) *Composition of the Earth's crust*—Methods should become available to derive information on the distribution of the earth's mass and possibly even the composition of its crust from observed perturbations in the satellite's orbit, provided the orbit is precisely known.

Satellite-borne Experiments

In addition to the experiments described above, the satellite affords a unique tool for observations of atmospheric and cosmic phenomena not directly susceptible to measurements on the earth. Many valuable ideas for possible satellite experiments have been presented by many private and public laboratories. The following experiments represent those now contemplated for satellite flights.

(1) *An experiment to measure the ultraviolet radiation from the sun at approximately 1,216 Angstroms*—This wavelength, the Lyman alpha line, is emitted by hydrogen, and represents a large part of the total ultraviolet radiation received from the sun.

Solar ultraviolet and x-radiation contribute most of the energy which is absorbed in the upper atmosphere. The energy of these radiations is first detected as ionization, affecting long-distance radio transmission, and causing other interesting phenomena such as airglow. Some of this energy eventually finds its way to lower levels in the atmosphere, where it affects the weather and climate. Solar ultraviolet data for any two-week period would be extremely useful, but should the period of the experiment include a solar flare or some other abrupt disturbance, the data would be of very great scientific interest. The Naval Research Laboratory is preparing this experiment.

(2) *A cosmic ray experiment*—The nature and origin of cosmic rays is not well known, nor is it easy to make measurements of their characteristics because of the screening effect of the earth's atmosphere. A Geiger counter in an IGY satellite will be used to measure the total incidence of cosmic rays at levels well above the atmosphere, without respect to charge, energy, or direction.

This simple experiment, prepared at the

State University of Iowa, will be the first long-continued measurement of cosmic rays over a wide area above the atmosphere of the earth. It will also establish a basis for future experiments, possibly involving more elaborate equipment and satellites extended over a greater range of latitudes.

(3) *An experiment to measure the earth's magnetic field*—The satellite can obtain synoptic data of the earth's magnetic field in space, sampling a wide range of altitudes in the range between perigee and apogee.

The scientific significance of magnetic field measurements lies in their ability to test the various hypotheses which have been made about streams of charged particles in the upper atmosphere and hence the nature of the field in the earth's high atmosphere. The Naval Research Laboratory is conducting this experiment.

(4) *An experiment to measure the terrestrial energy balance*—The principal energy input to the earth consists of radiation received from the sun. Some of this radiation is diffusely reflected by clouds, the remainder is converted to heat and is ultimately reradiated as diffuse radiation in the far infrared portion of the spectrum.

Since weather receives its heat input from the sun and exhausts by radiation to space, a better knowledge of these inputs and outputs would seem to be the most fundamental data one could expect to obtain.

Four special temperature sensing elements will be mounted, probably one at the end of each of the satellite's antennae. They will be coated with materials sensitive to radiation of various wave lengths, permitting three of the sensors to distinguish among, and measure, the solar visible, the reflected solar visible and the earth's infrared emission. The fourth sensor will incorporate a device sensitive to direction so that the effect of solar radiation in a directional beam can be distinguished from diffuse radiation. This experiment is being developed at the University of Wisconsin.

(5) *An experiment to observe the cloud cover of the Earth*—A technique which is likely to be important for possible future weather patrol satellites is presently being prepared at the Signal Corps Engineering Laboratories. This technique approximates a television picture of the cloud cover as contrasted with land masses and sea areas. Although the resolution of the system is expected to be only about six to thirty miles, a world-wide picture of the earth's cloud cover will be extremely valuable for studying weather phenomena.

(6) *Environmental experiments*—In addition to the 'hard-core' experiments listed above, a number of secondary environmental experiments are being prepared by the Naval Research Laboratory for inclusion along with one or more of the primary experiments. For the first satellite, the following are planned: surface and interior temperatures, skin erosion by micrometeorites and gas molecules, the number of encounters with micrometeorites above a predetermined minimum energy level, a rough measure of leakage rate in the event of puncture by a meteorite.

Secondary experiments are also planned for other satellites. In connection with the geomagnetic experiment, an extremely lightweight inflatable sphere has been developed. This sphere will be as visible as the original satellite and is expected to give air-drag data. The expandable satellite may well prove to be a valuable technique for possible future satellite work at higher altitudes. The National Advisory Committee for Aeronautics is preparing this experiment.

Status Report: Seismology, Gravity and Longitude & Latitude

The status of activity in each IGY area, approximately as of the opening of IGY, will be presented in the first three issues of the *Bulletin*. The status of the programs in seismology, gravity and longitude and latitude determinations is summarized below; other fields will be summarized in the next two issues.

Seismology Program

Studies of the Antarctic crustal structure will be made through the recording of earthquake waves. Stations for recording such waves have been set up at the Amundsen-Scott South Pole Station, Byrd Station, Cape Adare and on the Knox Coast at Wilkes Station, and all equipment has been installed. The station seismographs were procured by the U. S. Coast and Geodetic Survey; more specialized instruments were supplied by Lamont Geological Observatory and California Institute of Technology. In addition, portable equipment—supplied by Lamont Geological Observatory, Boston College, University of Wisconsin, and California Institute of Technology—is in use for study of the ice thickness and the underlying terrain. The first traverse, 650 miles from IGY Little America Station to IGY Byrd Station, has already been completed. The resulting seismic profile, begun 200 miles from Little America Station, showed ice depths increasing from 2000 to 7000 feet as Byrd Station was approached. In the immediate vicinity of Byrd Station, which is 5000 feet above sea level, ice thickness was found to be 10,000 feet.

Sea exploration is also planned as part of the USNC-IGY seismology program. Seismic refraction and reflection measurements will be made by Lamont Geological Observatory in traverses running almost the full length of the eastern and western Atlantic in coordination with vessels from Woods Hole Oceanographic Institution; the National Institution of Oceanography, England; Argentina; Brazil; and other South American countries. Sediment thickness and crustal layering will be determined. In the southeast Pacific, seismic exploration will be carried on by the Scripps Institution of Oceanography. Two vessels will be used for this work which will be performed in conjunction with studies of the deep currents. The cruise for this purpose is scheduled for November 1957–March 1958.

Simultaneous land and sea measurements are involved in the program of seismic exploration of coastal structures. In addition, measurements in sharply contrasting terrain—very high mountains and neighboring low lands—will be carried on in the Andes. A crustal strain seismograph has been installed in Santiago, Chile, and a second installation is practically complete at Huancayo Geophysical Observatory, Peru, constructed and installed under the supervision of Hugo Benioff, California Institute of Technology. These will be used to collect data on the accumulation of strain, whose release causes earthquakes.

Data on long period and other surface seismic waves will be collected by a widespread network of instruments. One long period instrument is now installed at the Coast and Geodetic Survey Seismological Observatory in Honolulu, and instruments have been shipped to the Belgian Congo and Trinidad. Nine additional installations are scheduled.

In the Arctic and North Atlantic Ocean regions, as well as several western Pacific islands, the U. S. Coast and Geodetic Survey will conduct studies of wave velocities, the location of earthquakes, crustal structure, and the relation of microseisms to storms. The stations for these studies are Thule, Greenland, and, in the Pacific, the islands of Guam, Truk and Koror. The stations at Guam and Truk have been in operation

since May 1956, and the installation at Koror was to have been completed in May 1957. A seismograph is being installed at Palmyra Island in cooperation with Scripps Institution of Oceanography.

Gravity Program

Overall objective of the IGY gravity program is to extend and complete the world network of gravity measurements. The number of pendulum bases for control purposes is being increased and gravimeter measurements extending from these bases intensified. The U. S. program is designed to aid materially in eliminating the serious gap in the international network of gravity observations which extends over most of the Southern Hemisphere and the polar regions.

Pendulum and gravimeter measurements have already been made in the past year—under the direction of George P. Woollard, University of Wisconsin—at Antarctic stations in order to establish base points for traverse teams using gravimeters. These teams will also measure ice thickness in support of seismic measurements. The Antarctic program will further contribute to studies of the topographic relief and isostatic compensation of the continent as a whole.

Some 12 pendulum and 40 gravimeter stations had been occupied by May 1957. The pattern ultimately to be achieved calls for occupation of stations in high latitudes and the establishment of meridional lines between the polar regions using Gulf compound quartz and Invar pendulums. These lines of observations will extend southward from Thule following the east coast of North and South America; southward from Shemya following the east Asiatic Coast through Australia to the Antarctic; southward from Hammerfest to Bodo where connection may be had with existing measurements; and southward from Barter Island to Fairbanks, where connection with existing measurements occurs. Lines of pendulum measurement already exist from Fairbanks, Alaska, to Mexico City, Mexico, and from Oslo, Norway, to Capetown, South Africa, established under the auspices of the Cambridge Research Center of the Air Force.

Gravimeter measurements will be made to establish ties between key pendulum base points, to establish regional networks of gravity observations where these are lacking or doubtful, and to integrate existing data into the world network.

The program calls also for improved determination of the rigidity of the earth at the tidal periods of approximately 12 and 24 hours. A highly sensitive recording gravimeter for the measurement of the tidal movement of the earth has already been used at various locations. It is sensitive to about one billionth of the value of gravity at the earth's surface, corresponding to a change in distance from the center of the earth of about one-eightieth of an inch. Using this instrument, which he helped develop, Louis B. Slichter, Director of the Institute of Geophysics, University of California, recorded a maximum amplitude of tidal motion of the earth of about four inches in November 1956 in Honolulu.

Submarine-based gravity measurements are projected, depending on the availability of submarine time. J. Lamar Worzel, Associate Director of the Lamont Geological Observatory, Columbia University, reports that a prototype instrument for this program constructed by Anton Graf, Munich, Germany, performed so well that, with suitable stabilized platforms now being developed, it should be adaptable for use on surface vessels—a development that would revolutionize the study of gravity at sea.

Latitude and Longitude Program

Objectives of this program include more precise determination of latitudes and longitudes, improved time determinations, and measurement of irregularities in the earth's rotation. A concomitant program centers on determinations of the moon's position in order to measure the moon's

motion for uniform time, detect variations in the earth's speed of rotation, and determine the geodetic relationship of widely-spaced points. The shape of the earth will also be studied in this program.

William Markowitz, Chairman of the USNC-IGY Technical Panel for the program, expected to receive Danjon impersonal astrolabes from France prior to July of this year. These, together with crystal clocks, will be used for latitude and longitude observations at the U. S. Naval Observatories at Washington, D. C., and San Diego, California, and at the U. S. Coast and Geodetic Survey Astronomical Observatory at Honolulu. Coordinates for these and other stations set up in the world-wide IGY program will be determined with anticipated errors of only a few feet. Map errors now range up to several hundred feet, and the positions of some islands are uncertain by as much as a mile.

Special cameras designed by Dr. Markowitz for moon-position determinations have been shipped to about 20 astronomical observatories around the world and are expected to be in operation by July of this year. The Markowitz camera takes a simultaneous exposure of the moon and surrounding stars, holding the moon's image fixed relative to the stars. This permits finding the position of the moon relative to the stars much more exactly than by other methods. Several observations of the moon on a single night by a station will determine the position of that station with reference to the center of the earth. From the positions obtained for a sufficient number of stations, the figure of the earth may be constructed.

Reports from Other Countries

Unless otherwise noted, the source of the following reports is the CSAGI IGY NEWS. Inquiries should be directed to Vice Admiral Sir Archibald Day, CSAGI Co-ordinator, 6 Avenue den Doorn, Uccle, Belgium.

Australia

The annual relief of the Australian National Antarctic Research Expeditions was recently completed.

New equipment installed at Macquarie Island includes a Dobson Ozone Spectrophotometer, an all-sky camera for automatic auroral photography, 'whistler' recording equipment and an additional cosmic ray meson telescope. Some modifications to the ionosphere sounder are being made without interruption of routine soundings.

Meteorological, geomagnetic and seismic observatory routines are continuing as previously.

The observing program at Mawson has been expanded through the installation of an ionosphere sounder, equipment for tracking meteor trails for upper wind determinations, an all-sky camera, phototheodolites for parallactic photography of the aurora, and a twelve counter cosmic ray neutron monitor, the records from which will supplement those from the two large meson telescopes. An active program of glaciological work and ice depth determination has been introduced.

Meteorological, seismic and geomagnetic observatory work is continuing at Mawson. Equipment for recording rapid magnetic fluctuations is being installed.

A new station, named Davis, was established at 68°34.6′S., 77°58.6′E. The program will cover meteorology, geology and operation of an automatic all-sky camera for auroral photography.

It is expected that all equipment will be operating before the end of March. Active participation in the IGY program at all three stations is assured.

Sweden-USA: Cosmic Ray Program

The Swedish ship *Lommaren* of the Trans-Atlantic Steamship Company, carrying the cosmic ray neutron monitor provided by the U. S. National Committee, under the direction of Martin Pomerantz of Bartol Research Foundation, is now making its second voyage to South Africa. The *Lommaren* left Göteburg, Sweden, on October 13, 1956, bound for Capetown, South Africa, with the monitor aboard, after preparatory testing of the equipment in the Baltic Sea. This was the first of several voyages that it will make in connection with studies of the geomagnetic latitude dependence of the cosmic ray intensity. These studies are related to the location of the geomagnetic equator.

A preliminary estimate of the location of the equator was made at the longitudes of crossing. However, at the most significant time—the crossing of the equator—a solar disturbance caused a world-wide decrease in cosmic ray intensity (a Forbush type decrease). Using data from other neutron monitor stations, however, it will be possible to make the necessary corrections for a more accurate location of the equator.

No worldwide disturbances of the cosmic ray intensity were reported at the time of the monitor's re-crossing of the equator on the return from its first voyage.

A continuation of the experiments with the same type of equipment is being carried on and is expected to extend throughout the IGY.

United Kingdom: Rocket Research

The first of the British Skylark rockets was fired at Woomera Range on February 13, 1957. The main object was to gain experience of its performance and at this firing no scientific observations were made.

As part of the British contribution to the IGY, research groups from five Universities and University Colleges, working under the auspices of the Royal Society and the Royal Aircraft Establishment of the Ministry of Supply, are cooperating in a program of scientific research, using specially designed instruments to be carried to heights up to 90 miles in the Skylark rocket, which will carry a payload of 100–200 lbs.

At the February firing, the 80-foot rocket launcher was depressed as far as possible so that the rocket flew a long flat trajectory. The reason for this approach is that the rocket has no form of guidance control. It possesses only three fixed stabilizing fins so that it is, in fact, a simple dart with a motor. Once launched it relies upon the built-in stability of the design to keep it going along the desired trajectory.

The scientific program is designed to investigate the pressure, density and temperature of the upper atmosphere, winds at very great heights, the ionosphere and night airglow. Various methods of measurement of each parameter will be used.

Among other things, it is proposed in connection with determining the sodium constituent of night airglow to produce sodium yellow fluorescence artificially by the ejection from the rocket of an ignited mixture of sodium and thermite at a chosen height. Special apparatus will be carried in the Skylark to obtain information on the E and the two F layers of the ionosphere by the use as probes of radio signals transmitted and received at ground level. Further experiments are planned for the measurement of air pressure, density and temperature at heights up to 80 miles, from readings of gauges mounted on the nose of the rocket itself.

Further information is obtainable direct from the Royal Society, Burlington House, Piccadilly, London, W. 1., England.

NATIONAL ACADEMY OF SCIENCES

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IGY BULLETIN

A monthly survey by the U. S. National Committee for the International Geophysical Year. Established by and part of the National Academy of Sciences, the Committee is responsible for the U. S. International Geophysical Year program in which several hundred American scientists are participating and many public and private institutions are cooperating.

Status Report: Meteorology, Oceanography & Glaciology

The IGY programs in meteorology, oceanography, and glaciology will constitute a coordinated study of the heat and water budget of the earth.

The meteorological program is directed at the study of major atmospheric circulation patterns and mass air movements, the exchange of heat between the tropics and the poles, and the remedying of important lacuna in weather data, particularly in the Antarctic area.

Oceanographic studies seek knowledge of the great circulatory systems of the oceans, of their deep currents, and of changes in sea level. Because the oceans are the earth's great storehouse of heat and moisture, studies of the transfer of heat and water, both within the atmosphere and hydrosphere and across the air-water interface, are a primary objective of IGY meteorology and oceanography programs. Many of these studies are synoptic in nature.

Similarly, some of the main purposes of the glaciological program are to investigate the dynamic properties and mass budgets of glaciers together with the exchange of mass and energy between glaciers and their meteorological environments. Other objectives are to determine locations, areal extents, and types of glaciers, to determine the pattern of regional climatic trends and the historical pattern of climatic changes as revealed by present and past glacier activity.

Meteorology

The IGY meteorology program involves a great expansion in facilities for gathering data on weather and climate. Many new meteorological stations have been established, primarily in Arctic and Antarctic regions and along the west coast of South America. Existing facilities have been improved with the introduction of new equipment designed to increase the accuracy and scope of observations.

Special studies in radiation and atmospheric composition are also being conducted during the IGY.

A pole-to-pole chain of meteorological stations, concentrated between 70° and 80° W, is essentially complete. Their observations will produce a meridional cross-section of weather and atmosphere. Similar data is being obtained by other nations along other meridional lines. The stations in continental United States, virtually all of

which were in operation previous to IGY, have been equipped for participation in IGY meteorological programs and are now functioning in those programs. Formal training was completed and observations begun on or about July 1 at the five jointly-operated South American Stations: Puerto Montt, Quintero, and Antofagasta, Chile; Lima, Peru; and Guayaquil, Equador. All stations in Alaska, the Canadian-US cooperative stations, and two Arctic drift ice stations are in operation.

Six USNC-IGY Antarctic stations have been fully equipped. All have been conducting standard observations, including 3-hourly surface observations; pilot balloon observations, when required for aircraft operations; continuous recording of surface temperature, humidity, pressure, precipitation, wind direction and velocity, and sunshine; and solar radiation.

A considerable amount of Antarctic weather data has already been gathered. A temperature of −100.4° F, the lowest recorded anywhere to date, was measured at the IGY Amundsen-Scott Station at the South Pole on May 11, 1957. On the same day Little America Station, only 600 miles distant, experienced 30° F. During April, May, and June of 1957, the average temperature at the South Pole was near −70° F. It is expected to be 20 to 30° lower at times during July, August, and September. Prevailing wind velocities averaged about 17 mph at South Pole Station during May, with a maximum of about 55 mph. A maximum velocity of about 78 mph was recorded on May 9 at Adare Station, and winds up to 100 mph occurred during stormy weather at Wilkes Station May 26–28.

Byrd Station reported 45.9 inches of snowfall for the period January 10 to March 31. During May, another 10.3 inches fell. Little America Station reported 22.1 inches for May.

By use of newly developed 800-gm balloons, the height of rawinsonde observations has been considerably increased. The discovery of a method of conditioning balloons by soaking them in warm diesel fuel prior to inflating has further increased their height potential. On May 13 a height of 91,000 ft was achieved at the South Pole Station. It is expected that heights of 100,000 ft or more will be reached. Antarctic stations, with the exception of Byrd, are taking observations twice daily at 0000 and 1200 GMT; Byrd Station is taking one such observation daily.

Approximately 100 other IGY stations, including about 28 operated jointly with other western hemisphere nations, are also equipped with these balloons and are following the same schedule of observations. At Quintero, Chile, the first rawinsonde observation was taken on June 4, and two-a-day soundings were begun on June 20.

At present, the IGY Antarctic Weather Central, staffed by meteorologists from three participating countries, is broadcasting the results of day-to-day synoptic weather analyses. These analyses, reaching all Antarctica and the southern hemisphere twice daily, are used for forecasting purposes. Raw data are received by Weather Central, located at Little America Station, from all of the other American Antarctic stations and from many stations operated by other countries.

Currently, the Weather Central staff prepares analyses of upper air charts at 700-, 500-, and 300-mb levels, and four sea-level charts. Thickness maps for the 1000/700 and 700/500-mb thickness, and time cross-sections for at least nine Antarctic upper air stations, are also being prepared. In addition, synoptic data accumulated and analysed at Antarctic Weather Central will ultimately help clarify the heretofore obscure influence of the Antarctic continent on the large-scale hemispheric and global circulation patterns. There is already some evidence confirming the previously expected existence of a deep cold cyclone over the central Antarctic land mass.

Time cross sections for more stations will be prepared as additional data becomes available. Pseudoadiabatic diagrams and

hodographs are prepared, as required, as well as other types of charts and diagrams.

Oceanography

The primary objectives of the IGY oceanographic program are to gain an understanding of the circulation of the ocean waters and of sea-level changes of both short and long duration and their relationship to other oceanic and atmospheric phenomena. For this work, more than 200 sea-level measuring stations, many of them newly established, and more than 70 ships are in operation or will be operated by approximately 35 participating countries.

The installation of measuring stations in the Atlantic, on selected islands and coastal promontories, is under the direction of the Lamont Geological Observatory. Stations already in operation in the Atlantic are in Barbados, Bermuda, Iceland, Fire Island, and on a Texas Tower. The Azores and Reunion stations will be in operation shortly. In the Pacific, Scripps Institution of Oceanography has installed stations on Marcus, Pitcairn, Rurutu, Canton, Johnston, Wake, and Napuka Islands. Other Pacific stations are being equipped. Of particular importance are the new stations in equatorial regions and the southern hemisphere, where observations have not been made in the past.

Besides determining variations in sea level, many of the island observatories are measuring ocean temperature and salinity to depths of 1000 ft. This will help determine to what extent changes in sea level are owing to volumetric changes, and to what extent they are caused by movements of water mass.

Van Dorn-type equipment at many stations will record waves of 5- to 15-minute duration; these waves, generally related to tsunamis, severe storms, and high-altitude atmospheric jet streams, are also believed to be present to a considerable extent at all times.

The main objectives of deep-water ship operations during IGY are to study the deep circulation of the Atlantic and Pacific Oceans and to conduct detailed, multiple-ship surveys of currents, temperatures, and chemical composition of ocean waters. Bottom topography and composition are also being studied. Most data will be accumulated over a two-year period. For practical purposes, however, such data may be considered synoptic in nature as the deeper currents are believed to be sufficiently slow-moving so that little or no change in the circulation system is likely to occur in that time.

Neutrally buoyant floats, recently developed by J. C. Swallow, of the National Institute of Oceanography of England, now make it possible to determine the depth of the more powerful, permanent ocean currents, and the depth, direction, and velocity of the deeper countercurrents.

Prior to the formal commencement of the IGY on July 1, 1957, several cruises had already been conducted in both oceans. The British research vessels *Atlantis* and *Discovery II* actually initiated the oceanographic program in March, when they met at Bermuda and then proceeded to the outer edge of the Blake Plateau, at about the latitude of Charleston, S. C., to conduct joint observations. The *Atlantis* measured deep temperature and salinity structure while the *Discovery* tracked neutrally buoyant floats at selected levels. The floats contained sound sources and tracking was done with hydrophones suspended from the bow and stern of the ship.

Shallower floats drifted to the northeast, as expected, and at expected velocities. At a depth of 2000 meters floats drifted only a few miles in four days, an amount not considered significant. At a depth of 2800 meters, however, the drift was 8 miles per day to the southwest. Thus, a level of minimum motion at about 2000 meters is indicated, with a rapidly-moving countercurrent below it.

On its way back to Plymouth, the *Discovery* achieved the most complete North

Atlantic profile to date, taking temperature, salinity, and oxygen measurements from the Grand Banks to the English Channel.

Meanwhile, in the US program, the Woods Hole research ship *Crawford* made four complete Atlantic crossings, two in the tropical North Atlantic and two over the tropical South Atlantic course profiled by the German ship *Meteor* 30 years ago. Comparison of the *Crawford* and *Meteor* profiles shows that although there were no striking changes in temperature and salinity, there has been a pronounced change in dissolved oxygen content. Especially near both ends of the profile, there is now more oxygen in the oxygen minimum layer and less in the deeper waters. Bottom water at depths below 4000 meters in the Antarctic western basin has lost as much oxygen as the deep water in the western basin of the North Atlantic. Presumably, water of sufficient density to renew the deeper waters is not at present being formed during the winters, either in the far north or the far south.

Subsidiary programs involving operation of the two drifting stations in the Arctic and measurement of CO_2 in the atmosphere and hydrosphere are also under way. Field operations begun on Fletcher's Ice Island in the spring of this year will continue for about six months. Standard oceanographic measurements, including temperature, salinity, heat flow, water depth, and other studies are being made. Similar studies will be carried out on Station A for one-month periods during the fall of 1957 and spring of 1958. Measurement of CO_2 in the atmosphere and oceans, being carried on jointly under the IGY meteorological and oceanographic programs, is designed to determine the amount of CO_2 in the atmosphere in order to establish adequate benchmarks for future trend analysis. (It has been suggested that the burning of fossil fuels may in time increase the amount of CO_2 sufficiently to affect our climate.)

Glaciology

IGY glaciological programs are now in progress to determine the volume of polar ice locked in the great ice sheets of Antarctica and Greenland and the floating ice of the Arctic basin, and to study the heat and water exchanges between these ice bodies and the atmosphere and hydrosphere. Snow stratigraphy, ice movement, temperature, and topography of the ice surface and the land beneath the ice are among the other things being studied in this program. Similar studies involve observation of the mass, budget, movement, and past and present environment of glacial ice.

Under study by United States teams are the McCall Glacier in the Brooks Range, Alaska, the Lemon Glacier near Juneau, Alaska, and the Blue Glacier in the Olympic Mountains, in Washington State. Work is also being done in the Alaska Range, Columbia Icefield, Cascade Mountains, and the Sierra Nevadas.

These glacial studies will yield knowledge on recent climatic changes and present trends in regions where meteorological records are poor or lacking.

Detailed studies will be made of the dynamics of movement, a complete accumulation-ablation cycle, and related problems in glacier morphology and chemistry. Glacier survey and census programs, involving much photogrammetric mapping, are being organized for Alaska and the continental United States.

A program for study of sea-ice physics and sea-ice-atmosphere heat exchange, under the direction of Phil E. Church, of the University of Washington, is under way on Drifting Station A in the Arctic Basin. Station A is on a large 7-foot-thick ice floe situated at about 80° N, 159° W.

The Snow, Ice, and Permafrost Research Establishment (SIPRE), of the Corps of Engineers, US Army, is undertaking a US-IGY program in Greenland. Henri Bader, of SIPRE, reports that in a 1700-foot drill

hole a temperature gradient of only 0.5° F. from 24.5° to 25.0°, per 1000 feet was measured. A second deep hole will be drilled this summer; the temperature gradient will be obtained and the rate of closing of the hole will be measured. Similar equipment is now in the Antarctic to be used to drill a deep hole in the vicinity of Byrd Station.

In the Antarctic, a 647-mile glaciology-seismology traverse from Little America to Byrd Station was completed in January 1957. The seismic profile of the traverse indicates an increase in ice thickness from about 1950 ft at the beginning of the traverse, 200 miles from Little America, to about 9850 ft, at Byrd Station. The elevation above sea level of the station is 4950 ft. Hence, the surface of the earth's crust on which the ice rests in this area is more than 4900 ft below sea level. This unexpected result reveals an interesting and hitherto unsuspected geological feature of the Antarctic continent, the significance of which is not yet known.

Deep pits have been dug at all IGY stations on the Antarctic ice cap for studies of snow stratigraphy, temperature, density and deformation, and for sampling for ice crystallography and chemical studies. The pits are ten or more meters deep. At a depth of ten meters, the annual ice-temperature amplitude is almost constant, varying no more than 0.5° C, and is within 1° of the mean annual atmospheric temperature. This provides a simple means of determining a primary climatic parameter without long-term meteorological observations.

The South Pole Station is using a snow mine for deep pit studies. The mine is now about 30 meters long and 6 meters deep. It is hoped that the mine will reach a depth of 30 meters to permit studies of structure and of the history of snow accumulation during the past several hundred years.

Snow stakes to measure movement of the ice have been set at Antarctic stations, and precipitation and ablation measurements are being recorded.

World Days During IGY

The synoptic objectives of the IGY program require that simultaneous observations be made in most of the disciplines throughout the world. Regular schedules to achieve this have been arranged. During some periods, however, an intensification in the observational programs is desirable and for this reason the World Days program was established. There are three classes of special days or periods during which special experiments or intensified observations will be undertaken: Regular World Days, World Meteorological Intervals, and Special World Intervals. (A calendar of these periods appears on the next page.)

World Meteorological Intervals (WMI) are series of ten consecutive days each in June, September, December, and March. They coincide exactly with two 'pentades' of the World Meteorological Organization and always include either a solstice or equinox, periods during which intensified meteorological observations are most desirable, at least on a predictable basis.

Regular World Days (RWD) are three or four days each month that are selected in advance. Two are consecutive days at the time of new moon; the others are at times of unusual meteor showers (Geminid, Perseid, Taurid, etc.), or near one of the lunar quarter phases. The RWD will also include the days of solar eclipse, with adjacent days for control purposes. For those types of observations which are insensitive to lunar phase or meteoric effects and for those observations which cannot be carried

INTERNATIONAL GEOPHYSICAL YEAR CALENDAR

1957-1958

JUNE 1957 (Advance Trial)

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SEPTEMBER 1958

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DECEMBER 1958

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JANUARY 1959

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23 24 25 26 27 28 29

World Meteorological Interval

① Regular world day

⓫ Day of total eclipse

⓿ Regular world day at new moon

⑫ Regular world day with unusual meteoric activity

Ⱥ Unusual meteoric activity (but not world day)

Final Calendar of Regular World Days (RWD) and World Meteorological Intervals (WMI) during the International Geophysical Year 1957-1958

Adopted by CSAGI, September 1956 and edited by

CSAGI SECRETARIAT
3, AVENUE CIRCULAIRE, UCCLE-BELGIUM

out continuously throughout the IGY period, the RWD should constitute a representative sample of the IGY period and the resulting concentration of effort should be useful in the interpretation of results in all disciplines.

Special World Intervals (SWI) are designated on a day-to-day basis by the IGY World Warning Agency in the United States, acting with the advice of forecasting centers throughout the world. A period of Alert will be declared whenever solar activity is unusually high and significant geomagnetic, auroral, ionospheric, or cosmic ray effects are probable. During the period of Alert, an SWI may be declared (at 1600 UT to commence at 0001 UT the following day) whenever the probability is high that an outstanding geomagnetic storm, with associated effects in other disciplines, will begin within a few hours. The periods of Alert and SWI will continue in effect until terminated by the World Warning Agency. An effort will be made to predict only the most outstanding disturbances in the designation of the SWI.

An example of the operation of the World Warning Agency occurred when a large solar flare, of importance 3, was reported by Krasnaya Pakhra Observatory, Moscow, USSR, as having begun at 0700 UT June 28, 1957. Although this was the only report on the flare, its importance was such that the World Warning Agency declared a state of Alert beginning at 1600 UT the same day. This was followed, on June 29, by designation of an SWI commencing at 0001 UT July 30. The SWI continued until 2359 UT July 3, and the alert ended on July 6. A very large magnetic storm began about 0400 UT June 30, lasting until about 0100 UT July 2. During the magnetic storm great auroral activity was reported, and on July 1 communications were seriously disturbed; the quality figure for a 6-hour period that day was 1, the lowest in many years.

Rockets & Satellites: Radio Tracking System

This report, one of a series on the USNC-IGY Earth Satellite Program, deals with radio tracking of the satellites. The Academy's IGY Committee assigned responsibility for the scientific radio tracking program to the Naval Research Laboratory, developer of the Minitrack system. The illustrations and much of the technical information in this discussion are extracted from reports on the subject by J. T. Mengel, who is in charge of the Minitrack Program at the Naval Research Laboratory.

Once an earth satellite has been launched, the next major task will be to find it. The small satellite will not be observable by optical means except during periods just before sunrise or just after sunset, when the satellite is illuminated by the sun against a dark background sky. Optical observation is further restricted to clear weather.

A radio transmitter carried in the satellite is expected to make the satellite observable by day or night, in poor or clear weather. Moreover, a radio receiving antenna will have a larger beamwidth, or field of view, than an optical system depending upon detection of sunlight reflected from the satellite. Therefore, the satellite will be found more easily by radio techniques.

The prime purpose of radio tracking will be to prove that the satellite is in fact orbiting and to obtain orbital data for the computation of preliminary ephemerides. Only by means of such ephemerides will the precision cameras to be used in the optical system be able to track the satellite. Moreover, radio observations of the satellite, although less precise than those by optical means, will have significant scientific value. In addition to providing information on the

precise relative distances between the tracking stations, radio observations will be more closely spaced and more frequent than the optical observations. This characteristic of the radio data will be especially valuable if the satellite is short lived; it is also expected to be important for disentangling perturbations due to gravitational anomalies.

Minitrack System

The particular system which NRL has developed is accurate enough to measure change of position as well as position. This means the satellite can be 'tracked' in addition to being found by its radio signal. And, since the transistorized satellite-borne transmitter is necessarily of minimum size and weight, the overall system has been named Minitrack. The Minitrack transmitter will normally be operated at power levels in the range of 10–80 milliwatts, depending upon the particular on-board experiments being carried. The mercury cell batteries are expected to furnish electric power for about three weeks. The transmitter uses transistors with crystal control for frequency stability.

The satellite signal is transmitted at a frequency of 108.00 megacycles. While ionospheric effects are quite large for frequencies to about 30 megacycles, these effects, although greatly reduced, are still significant at 108 megacycles; indeed, they constitute the basic limitation on the accuracy of the Minitrack system. On the other hand, these effects are not entirely detrimental. The displacement which the ionosphere imposes upon the radio image of the satellite gives a crude measure of the number of ions between the satellite and the receiving station. Ionization in the atmosphere will also affect the Doppler shift of radio signal frequency caused by motion of the satellite transmitter relative to the ground receiver. This presents another possibility for obtaining approximate data on the ionosphere.

Minitrack determines the angular position of the satellite by employing a radio phase comparison technique. Unless the satellite happens to be located in a bisector plane between a pair of receiving antennas, the radio signal from the satellite will have to travel a slightly different distance to each of these antennas. The relative phases of the received signals are dependent upon the difference in these distances and therefore upon the angular position of the satellite with respect to the plane bisecting the pair of antennas.

For example, Figure 1(a) shows two such antennas. The radio signal travels the same distance in going from the satellite to point P_1 as it does in going to antenna A_1. Therefore, the number of wavelengths is the same for both paths and the phase of the signal at point P_1 is the same as the phase of the signal at antenna A_1. The additional distance which the signal must travel to reach antenna A_2 can be measured by examining the phase of the signal at antenna A_2 relative to the phase at point P_1 (or at antenna A_1).

Since $A_1A_2P_1$ can be considered a right triangle, the angular position of the satellite from the zenith can now be calculated from the known separation of the antennas and the measured distance P_1A_2. A second pair of antennas placed with their baseline 90° to the first pair would allow calculation of a second angle. These two angles would determine completely the direction of the satellite from the antennas (see Figure 1(b)).

If the antennas are wider apart, as in Figure 1(c), the angular position can be determined with greater precision. The disadvantage of this arrangement is that uncertainties are introduced as to the number of wavelengths contained in the distance P_2A_1. The actual Minitrack antenna array consists of a combination of closely spaced and more widely separated antennas. The baseline of the closely spaced antennas is short enough that the phase difference is never ambiguous for any position of the satellite within the beamwidth of the system.

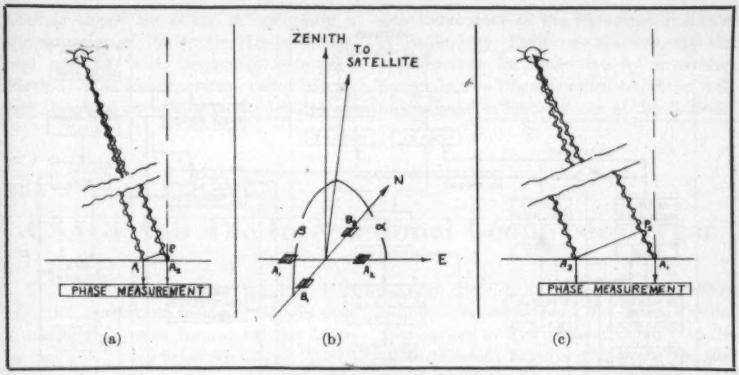

FIG. 1. *Phase Measurement in the Minitrack System.*

Minitrack Stations

The field of view, or antenna beamwidth, of the Minitrack array of receiving antennas will be 100° in a north-south direction and 10° in an east-west direction. This fan-shaped intercept pattern was especially designed for the Minitrack stations which string from north to south, approximately along a 75th meridian 'picket fence,' at the following locations: Blossom Point, Maryland; Savannah, Georgia; Havana, Cuba; Mt. Cotopaxi, near Quito, Ecuador; Lima, Peru; Antofagasta, Chile; Santiago, Chile.

Coolidge Field, Antigua Island, was chosen as the site of an eighth station, so that observational data would be available soon after launching. The ninth station is to be located at San Diego, California, for a favorable observation of the satellite on its first orbit. A tenth station, to be located at Woomera, Australia, will extend observations longitudinally. If all the equipment is operating properly, there is better than a 95% chance that the satellite will be observed by at least one of the radio tracking stations during each orbit.

The US Army is handling the communications arrangements between the radio tracking stations and the Washington computation center, which will compute and progressively refine the satellite orbit from the radio tracking data. The US Army also has responsibility for the construction of station facilities and operation of the equipment at the Savannah, Havana, and four South American sites. The Australian National Committee will perform these functions for the Woomera Station. The various other countries in which radio tracking stations are located are supporting these stations extensively through their IGY National Committees and the Inter-American Geodetic Survey. The US Air Force will operate the Antigua station, while the Naval Electronics Laboratory will man the San Diego site.

The Havana station is expected to be set up and ready for calibration by the end of September 1957. All other stations are to be ready for calibration before the middle of September. Training has been in progress since March of this year. Instructors at the prototype training station at Blossom Point are being supplied by the US Army.

Receiving Equipment

The equipment for this prototype station was built by the Naval Research Laboratory. The equipment for the remaining stations is being built commercially to the

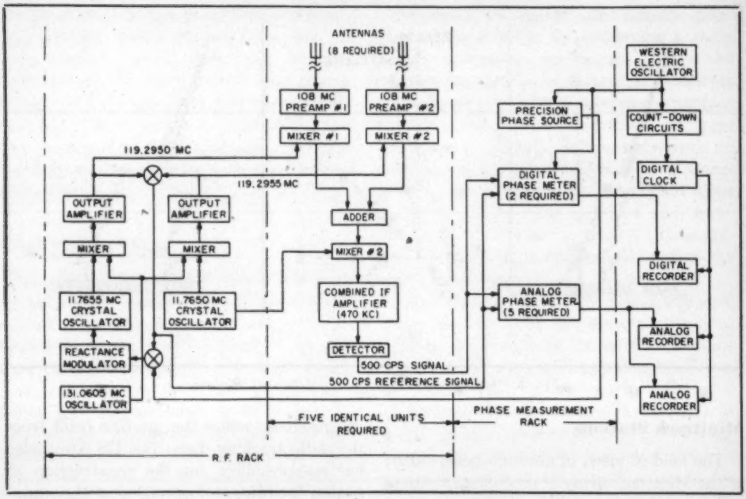

FIG. 2. *Minitrack Receiver Block Diagram.*

same design. The basic characteristics of the Minitrack receiving system are indicated by the block diagram, Figure 2.

Two very weak signals of 108 mc, but differing in phase, are received at a pair of antennas. Each of these signals is mixed (through a double superheterodyne system) with highly stable, locally generated reference signals so that the beat frequency developing from the signal of one antenna is 470 kc and that from the other is 469.5 kc. The signals at this frequency can be amplified in a common amplifier to a level of several volts without loss of precision. They are fed to a square-law detector which yields a single 500-cycle signal bearing the same phase difference relative to the internal reference as was originally present in the 108 mc signals received at the two antennas.

A system of precision electrical phase comparison circuits converts the 500-cycle signal into angular direction data of both digital and analog types. Each Minitrack station contains five phase comparison channels of this type, as follows: east-west 'fine' from the east-west 500-foot baseline; north-south 'fine,' from the north-south 500-foot baseline; east-west medium ambiguity resolution, from the east-west 64-foot baseline; north-south medium ambiguity resolution, from the north-south 64-foot baseline; north-south coarse ambiguity resolution, from the north-south 12-foot baseline.

The Minitrack signal also serves as a carrier for the telemetered data from the experiments contained in the satellite. These experiments are also dependent upon the tracking data for identification of geographical position through a common time base.

Other Radio Tracking Systems

Two less elaborate radio tracking systems have been developed for construction and operation by radio amateurs or by professional or student groups. One of these,

also developed by NRL, is essentially a simplification of the prime Minitrack system and has been designated Minitrack Mark II. The second system, called Microlock, has been developed by the Jet Propulsion Laboratory of the California Institute of Technology. These two systems, and the opportunities for their use by interested groups in the US and other countries, will be discussed in future issues of the *Bulletin*.

CSAGI And The International Geophysical Year

The Special Committee for the IGY (Comité Spécial de l'Année Géophysique Internationale) was formed by the International Council of Scientific Unions (ICSU) from representatives of members of the organizations adhering to ICSU to develop and coordinate a world program. This Committee met for the first time in October 1952. In January 1952, the Executive Committee of ICSU circularized national adhering organizations urging the formation of national committees. By January 1953, thirteen national committees had been formed; this number has increased until at the present time there are about 64 participating countries and perhaps another dozen cooperating.

In 1955 the CSAGI established a small permanent secretariat in Brussels to assist the Special Committee in its task of coordinating the national programs. This has been accomplished principally by means of international meetings of representatives of national committees. Such meetings were held in Brussels in 1953, in Rome in 1954, in Brussels in 1955, and in Barcelona in 1956. In 1956, Adjoint Secretaries for the Antarctic, Arctic, Eastern Europe, South Africa, and the Western Hemisphere were appointed to assist in the development and coordination of the IGY program in their regions. Four Antarctic Regional Conferences have been held—the first in Paris (July 6–10, 1955), the second in Brussels (September 8–14, 1955) and the others in Paris (July 1956 and June 1957). An Arctic Conference was held in Stockholm (May 22–25, 1956). Conferences were held for the Western Hemisphere in Rio de Janeiro (July 16–21, 1956); Eastern Europe in Moscow (August 20–25, 1956); South Africa (February 11–15, 1957) and the Western Pacific in Tokyo (February 25–March 2, 1957).

The officers and members of CSAGI are listed below; members reflect representation on behalf of various ICSU unions and similar international technical organizations.

Officers and Bureau Members: Professor Sydney Chapman, President; Dr. Lloyd V. Berkner, Vice President; Dr. Marcel Nicolet, Secretary-General; Professor V. V. Beloussov; Professor J. Coulomb.

International Astronomical Union (IAU): Professor A. Danjon, Dr. Y. Öhman.

International Union of Geodesy and Geophysics (IUGG): Professor V. V. Beloussov, Professor J. Coulomb, Professor G. Laclavère, Dr. V. Laursen, Professor N. V. Pushkov, Professor P. Tardi.

International Scientific Radio Union (URSI): Dr. W. J. G. Beynon, Professor M. Boella, Father P. Lejay, Mr. A. H. Shapley.

International Union of Pure and Applied Physics (IUPAP): Dr. J. A. Simpson, Dr. S. Vallarta.

International Geographical Union (IGU): Sir James Wordie.

International Union of Biological Sciences (IUBS): Dr. A. F. Bruun.

World Meteorological Organization (WMO): Dr. T. E. W. Schumann, Professor J. Van Mieghem.

International Consultative Committee for Radio Communications (CCIR): Professor B. van der Pol, Mr. J. van der Mark.

CSAGI also designated fourteen of its members as Reporters to assist in the coordination of the national programs within each discipline as follows:

Discipline	Reporter	Union
World Days	A. H. Shapley	URSI
Meteorology	J. Van Mieghem	WMO
Geomagnetism	V. Laursen	IUGG
Aurora and Airglow	S. Chapman	ICSU
Ionosphere	W. J. G. Beynon	URSI
Solar Activity	Y. Öhman	IAU
Cosmic Rays	J. A. Simpson	IUPAP
Longitude and Latitude	A. Danjon	IAU
Glaciology	J. M. Wordie	IGU
Oceanography	G. Laclavère	IUGG
Rockets and Satellites	L. V. Berkner	ICSU
Seismology	V. V. Beloussov	IUGG
Gravity Measurements	P. Lejay	URSI
Nuclear Radiation	M. Nicolet	

IGY Annals Announced

CSAGI has arranged for the publication of the *Annals of the International Geophysical Year* by the Pergamon Press, Ltd., London. The Annals are to constitute a central record of IGY activity and proceedings and of technical manuals.

Volume I will be an Introductory Volume to the International Geophysical Year. Volume II will comprise Reports of Proceedings of the International Geophysical Year. Volumes III-VI will consist of technical manuals in the various disciplines.

Volume III, first to be published, is an Instruction Manual For Ionospheric Studies in the International Geophysical Year. It will consist of four instruction manuals for the Ionosphere Section and will be completed in two issues of the Annals. The first issue contains Part I—"Ionospheric Vertical Soundings;" the second will contain Parts II, III, and IV, and will contain "The Measurement of Ionospheric Absorption," "The Measurement of Ionospheric Drifts," and "Miscellaneous Radio Measurements."

The publisher expects to bring out a maximum of four to six volumes of the Annals, averaging about 400 pages each, during 1957 and 1958. Subscription rates are $17 per volume. Inquiries may be directed to the Pergamon Press, Ltd., 122 East 55th Street, New York 22, N. Y., or 4 & 5, Fitzroy Square, London, W. 1.

World Data Centers

With more than 60 nations participating in the IGY, with some 10,000 scientists and observers taking measurements and observations at more than 2000 stations distributed around the earth and from pole to pole, it is apparent that vast quantities of data will be acquired. A first step in the utilization of the results of IGY is the orderly compilation of these data, their safe and proper storage in accessible centers, and their indexing. These problems have been the subject of international deliberations for some two years.

At the CSAGI meeting in Brussels in the fall of 1955, a proposal was put forward for the centralization of all IGY records and data in world centers which would assure that the data were properly stored and catalogued and that they were readily available to geophysicists for research. Several nations indicated a willingness to undertake this responsibility or to provide explicit centers for explicit disciplines. CSAGI examined these offers and a plan has now been developed whereby the United States will assume responsibility for IGY World Data Center A, the USSR will assume responsibility for Center B, and Center C will be dispersed throughout Western Europe and the Pacific.

Plans for the United States World Data Center have now been developed. A Data Coordination Office is now established in the National Academy of Sciences to direct this effort, and the Academy has selected archive centers for the respective disciplines.

Each of the following institutions has accepted responsibility for the discharge of this important aspect of the international IGY program:

Discipline	Institution
Aurora I (Visual Observations)	Cornell University
Aurora II (Instrumental Observations)	University of Alaska
Airglow, Ionospheric Physics	National Bureau of Standards (CRPL)
Cosmic Rays	University of Minnesota
Geomagnetism, Gravity, Seismology	U.S. Coast & Geodetic Survey
Glaciology	American Geographical Society
Latitude and Longitude	U.S. Naval Observatory
Meteorology	National Weather Records Center
Oceanography	Texas A. & M. College
Solar Activity	University of Colorado
Earth Satellites and Rocketry	National Academy of Sciences

Detailed plans for the organization and operation of these Centers are now being developed. International agreements have been made whereby data which reaches one Center will be exchanged with other Centers abroad thus assuring that each Center will comprise a complete repository of the IGY data.

Data Center B, to be operated by the USSR, is to be divided into two sub-centers:

Sub-center 1, Novosibirsk: meteorology, longitude and latitude, glaciology, oceanography, seismology, and gravity.

Sub-center 2, Nizmir: aurora and airglow, ionospheric physics, solar activity, cosmic rays, and geomagnetism.

Data Center C, to be operated by several nations in Western Europe and the Pacific, consists of the following sub-centers:

Discipline	*Country*
Geomagnetism	Denmark and Japan
Aurora	Sweden and Great Britain
Airglow	France and Japan
Ionosphere	Great Britain and Japan
Solar Activity	Switzerland, Italy, Great Britain, France, German Federal Republic, and Australia
Cosmic Rays	Sweden and Japan
Glaciology	Great Britain
Meteorology	World Meteorological Organization
Seismology	International Central Seismological Bureau (Strasburg)

The tasks of the data centers will begin very soon after July 1957 and will continue through 1959. By then most of the data will be properly stored, catalogued, and available for consultation by scientists.

USSR Rocket and Satellite Program

In the latter part of June, CSAGI received and distributed the USSR Rocket and Satellite Program for the IGY. Text of the USSR document states that preliminary proposals call for use of both rockets and satellites to study these aspects of the upper atmosphere: (1) structural parameters, (2) optical properties, (3) ultraviolet and X-ray radiation and absorption, (4) corpuscular solar radiation and aurorae, (5) cosmic rays, particularly their origin and intensity and the periods of time the particles wander in space, (6) ionospheric physics, (7) magnetic fields, (8) micrometeors and meteorites, and (9) physical and chemical processes in the upper air—through introduction of chemical reagents into the atmosphere.

Rocket firings will be made along the meridional belt 50°–60°E in three zones, the Arctic (Franz Joseph Land), the middle latitudes of the USSR, and the Antarctic (mainly in the area of Mirny). Total number of firings indicated is 125: 25 in the first zone, 70 in the second, and 30 in the third. The launchings will be evenly spaced throughout the IGY, the program states, although none are scheduled for the Arctic zone until 1958. The rockets will carry instrumented "containers" to heights ranging up to 200 km.

Satellites will be launched from the USSR, the report says, at a small angle to the meridian. Thus, a nearly polar orbit will be attempted, and a successful satellite will be observable in all areas of the earth except "the central areas of the Arctic and Antarctic." No indication is given as to the number of satellites whose launching will be attempted nor are launching dates specified. However, the statement with respect to even spacing of rocket firings is also applicable to satellite launchings.

Fourth Antarctic Conference

The Fourth Antarctic Conference, Paris, June 13–15, 1957, was attended by delegates from participating committees of eleven nations: Argentina, Australia, Belgium, Chile, France, Great Britain, Japan, New Zealand, Union of South Africa, USSR, and USA.

Presided over by the CSAGI Adjoint Secretary for the Antarctic, Colonel Georges Laclavère, the Conference opened with a session devoted to scientific papers on various geophysical problems of the Antarctic. Reports on the status of various committee programs were presented. Working groups on radio communications, logistics and mutual support, the weather central, and meteorology met, reviewing the status of operations in these areas and finalizing arrangements for the IGY period.

A proposal by New Zealand, that an informal symposium be held in New Zealand during the period February–March, 1958, when Antarctic scientists wintering-over this season would be returning, was received favorably by the Conference. A similar proposal from Argentina for a symposium in the spring of 1959 was endorsed by the Conference. IGY groups in New Zealand and Argentina were authorized to proceed with the fuller development of their plans.

The question of an extension of Antarctic research beyond the IGY period was discussed. There was unanimous recognition of the scientific value of continued Antarctic investigations. Taking into cognizance, however, the fact that CSAGI officially terminates at the end of IGY, the Conference adopted the following recommendation:

"Considering the scientific importance of further observations in the Antarctic after the end of the IGY to best achieve the scientific investigations carried out on this occasion and to make use of the investments and observations made in the various stations.

"Recommends that the Bureau of CSAGI at its next meeting forwards to the ICSU Executive Board the recommendation expressed as follows:

"That ICSU appoints a scientific committee to examine the merits of further investigations in the Antarctic, covering the entire field of science and to make proposals to ICSU on best way to achieve such program. That in view of the desirability of avoiding an interruption in the current series of IGY investigations in Antarctica, ICSU takes immediate action in order that the finding be available by the middle of August."

Antarctic Notes

Weather at the South Pole

During the past Antarctic summer, the IGY Amundsen-Scott South Pole Station observed temperatures ranging generally between 0° and −20°F. By the end of February, the temperature had fallen rapidly to −67°, by the end of March to −87° and, on May 11, to a new world record of −100.4°F.

The record low came after two days of steadily falling temperatures. Highest read-

ing during May was −30.1°F on the 15th while the average temperature for the month was −68.2°F. (A more recent communication reports that Ronald C. Taylor, using climatological data and empirical relationships, has made a minimum temperature forecast for the Pole of −112°F, plus or minus 3°.)

A few hundred feet above the surface, the temperature increases as much as 50°F, then decreases with height to the tropopause three miles above the polar plateau where the temperature is still slightly higher than at the surface.

The temperature inside the tunnels surrounding and interconnecting the buildings at the South Pole Station lags behind the outside temperature, but at the time the record low was reached this too was already close to −70°F. Moist air from the buildings caused fog in the tunnels, reducing visibility to a matter of yards. Outside, the air was clear. The temperature of the snow on May 11 was −101.5°F. Snow in fine crystal form has been surprisingly frequent but accumulates slowly.

In addition to record low temperatures, the weather during May was characterized also by record high winds. This unique feature resulted in a very high chill factor. The average wind speed during May was 17 mph with peak gusts of 54 mph on the 25th. Upper winds over the South Pole have been variable and quite strong—as much as 130 mph.

Neutron monitor studies

A neutron pile monitor designed and built under the direction of John A. Simpson, Enrico Fermi Institute for Nuclear Studies, University of Chicago, was installed on the icebreaker USS *Arneb* and operated throughout Deep Freeze I and II, 1955–56 and 1956–57, respectively. This work is part of a larger study of secondary radiation from the low-energy portion of the primary cosmic ray spectrum. Approximately 75% of the cosmic ray particles to which the neutron pile monitor is sensitive fall within a magnetic rigidity range where the geomagnetic field of the earth may be used as a particle rigidity analyser. Neutron pile monitors have been installed at various locations in differing magnetic latitudes; the monitor on the icebreaker has supplied information on the variation of cosmic ray intensity with latitude changes which can be interpreted to give the variation of the earth's geomagnetic field and the location of the geomagnetic equator in space. United States Navy Task Force 43 has been most cooperative in rescheduling the route of the *Arneb* both going to and returning from the Antarctic in order to provide crossings of the geomagnetic equator at desirable locations.

On February 23, 1956, occurred a solar flare with associated large increase in cosmic ray intensity; this was only the fifth time that such an association had been observed. The *Arneb* was in the harbor of Wellington, New Zealand, at the time and thus the neutron monitor aboard provided an extra station in the network. The significance of the Wellington observations is that Wellington is outside of the impact zone, as is Chicago, Illinois. These two widely separated stations yielded precise information on the time of onset, rate of rise, the maximum intensity, and the rate of decline of the temporary increase.

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Radiocarbon Evidence on the Dilution of Atmospheric and Oceanic Carbon by Carbon from Fossil Fuels

H. R. Brannon, Jr., A. C. Daughtry, D. Perry, W. W. Whitaker, and M. Williams

Abstract—The dilution of atmospheric carbon dioxide by carbon dioxide from fossil fuels is estimated to be about 3½ pct, on the basis of radiocarbon assays of tree rings of known ages from several trees of different genera, after allowance has been made for effects attributable to ecological differences. The cumulative mass of fossil carbon dioxide released to the atmosphere is 3.3×10^{17} gm, equivalent to about 14 pct of the carbon dioxide in the atmosphere. Based on these data, the fractional part of the atmospheric carbon dioxide which enters the ocean each year is estimated to be 0.062. Radiocarbon assays of several nineteenth-century marine shells and of their modern counterparts indicate a one to two per cent dilution of shallow oceanic carbonates by carbon dioxide from fossil fuels. Use of these data in a simplified mathematical model of atmosphere-ocean yields information on mixing times of the ocean.

Introduction—The effects of addition to the carbon cycle in nature of carbon dioxide from industrial activities have been the subject of speculation in several fields of science. Of particular interest is the fate of the enormous quantity of carbon dioxide which has been introduced into the atmosphere since the beginning of the industrial revolution in the 19th century, and the manner in which the added carbon dioxide has been distributed in the carbon cycle. Although appreciable amounts of carbon dioxide have undoubtedly been added from soils by tilling of land, apparently a much greater amount has resulted from the combustion of fossil fuels.

Callendar [1940] pointed out that direct measurements of the carbon dioxide concentration in air, made over a number of years by various investigators, indicate a significant increase in concentration over the period 1866–1935. From this he concluded that most of the carbon dioxide from the industrial revolution has remained in the air and, consequently, that the rate of absorption of carbon dioxide by the oceans is very slow. *Hutchinson* [1954] suggested that the radiocarbon content of woods from trees which have lived during the industrial revolution might throw light on the dilution of atmospheric carbon dioxide by carbon dioxide from the combustion of fossil fuels. *Suess* [1954] at about the same time determined the radiocarbon content of tree rings of known ages from several trees. These results indicated a dilution of about 3½ pct. In later work *Suess* [1955], on the basis of results on additional samples, revised the probable dilution downward to less than one per cent and ascribed the former higher indicated dilution to localized effects of industrial activity.

Within the last several years there have been rapid advances in the methodology of radiocarbon assay, particularly as it pertains to radiocarbon dating. As a result, it is possible today to make routine radiocarbon assays in which the statistical uncertainty is less than one per cent for contemporary concentrations of natural radiocarbon. In view of such precision, a knowledge of the dilution effect becomes important in the precise radiocarbon dating of carbon-containing materials. It was to gain knowledge of the dilution effect in both plant material and shallow oceanic carbonates that the investigation described in the following sections was undertaken. In all of the experimental work, radiocarbon assays were made by proportional counting of the sample as carbon dioxide gas, contained in the counter under a pressure of five atmospheres absolute [*Brannon, Taggart,* and *Williams,* 1955]. The same counter was used for all assays. In the preparation of each sample the conversion to carbon dioxide and the recovery of the carbon dioxide were virtually complete, assuring an absence of effects due to isotopic fractionation. The results in all cases have been expressed in terms of net counts per minute for the particular counter employed. No attempt has been made to convert the results to a form which would reflect the absolute disintegration rate per unit mass of carbon.

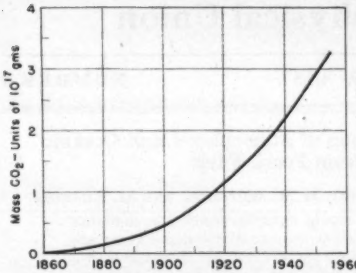

FIG. 1 — Cumulative carbon dioxide released to atmosphere by combustion of fossil fuels

Appraisal of carbon dioxide production from fossil fuels—Although various estimates have been made of the cumulative amount of carbon dioxide released to the atmosphere since the beginning of the industrial revolution by the combustion of fossil fuels, it was deemed desirable to reappraise both the total amount and the rate at which it has been introduced into the atmosphere.

The greater part of this carbon dioxide, by far, has been attributable to the burning of coal. Perhaps the best data suitable for the estimation of the contribution from coal are given by *Putnam* [1953] for world-wide consumption since the year 1860. His values are expressed in terms of heat content of coal consumed, so that proper weight may be considered to have been given to the rank of the coal. The conversion of Putnam's figures for coal consumption to mass of carbon dioxide produced may be accomplished by means of a factor relating carbon content to heat content of coal. Perhaps the most reliable data for the consumption of liquid petroleum are those given in a publication of *DeGolyer* and *MacNaughton* [1955]. The carbon dioxide produced by combustion of petroleum may be estimated by use of an average value for the carbon content of liquid petroleum. Although the mass of carbon dioxide produced by the combustion of natural gas is relatively minor, this may be approximated by use of an average carbon content of natural gas and of a ratio of gas to oil produced. This ratio may be assumed to have increased continuously from about 1910 to the present.

Figure 1 shows an estimate of the cumulative amount of carbon dioxide released to the atmosphere by the burning of fossil fuels made by use of the foregoing data and assumptions. The cumulative production to date, approximately 3.3×10^{17} grams of carbon dioxide, is equivalent to about 14 pct of the total amount of carbon dioxide in the atmosphere. This is somewhat less than an estimate made by *Putnam* [1953], and is slightly higher than an unpublished estimate made by Harrison Brown (private communication). Although no values of carbon dioxide equivalency are contained in a paper on total fossil fuel production by *Hubbert* [1956], application of reasonable carbon contents of coal and of petroleum to Hubbert's estimates of production would likely result in an estimate of total carbon dioxide production which would be slightly higher than that of Figure 1. It may also be noted that the estimate made by *Callendar* [1940] for carbon dioxide production between 1900 and 1935 is somewhat higher than that shown by Figure 1.

The curve of Figure 1 is not of simple exponential form. The portion from 1860 to about 1910 approximates an exponential form, but the part of the curve from 1910 onward deviates progressively from the exponential. The deviation is such that less carbon dioxide has been produced than would be expected from an exponential relation fitted to the early part of the curve. Application to the curve of combustion efficiency factors given by Putnam, however, yields a curve which follows closely an exponential form. From this it may be inferred that improvements in efficiency of utilization of fuels achieved during the last several decades have resulted in appreciably less consumption of fuels than would have been the case otherwise.

Evidence on dilution of atmospheric carbon dioxide—In investigating the dilution of atmospheric carbon dioxide and, consequently, of the carbon contained in vegetation by carbon from fossil fuels, the method of attack was essentially that followed by *Suess* [1954, 1955]. Radiocarbon assays were made of tree rings of known age, including rings of very recent age.

The selection of the woods for investigation posed a problem. Obviously, if an attempt were made to include all types of woody plants from all possible environments in which they are found, the number of samples would be prohibitively large. The decision was made, therefore, to choose only a very limited number of woods, but, in the selection, to attempt to choose samples which might yield definitive results. In particular, the samples were selected to represent extremes in environment and ecology.

The woods investigated were oak, gum, 'cypress' (*Taxodium*), and Douglas fir. The oak and gum samples were obtained from locations in eastern Texas approximately 75 miles north of Houston.

The cypress sample came from the swamps of south Louisiana, and the Douglas fir, kindly furnished by Edmund Schulman, was from the Rocky Mountain region. In all cases the samples were obtained from areas relatively remote from the centers of industrial activity in which there might be abnormally large concentrations of dead carbon released to the atmosphere from the utilization of fossil fuels.

Results of radiocarbon assay of samples of these woods of various ages are given in Table 1. An examination of the results reveals several features of interest. Perhaps the most conspicuous of these is the variation of the extrapolated contemporary assay of the four woods. This variation may be seen more clearly when the averages of the contemporary assay, extrapolated from the actual assays of samples 50 years or more old, are tabulated (Table 2). In the computation of the average extrapolated assay for the cypress, it is probably justifiable to disregard the data obtained from assay of the 600-year ring on the ground that this ring was in close proximity to the central cavity common in the swamp cypress, and therefore was particularly vulnerable to the influence of intrusive carbon. The difference in extrapolated assays of the Douglas fir and cypress is roughly six per cent.

Although the possibility cannot be ruled out that the differences in the extrapolated contemporary assays are attributable to differences in physiological behavior peculiar to the diverse genera, it seems more reasonable that the differences in assays are a reflection of the different ecological conditions under which the trees grew.

The Douglas fir generally grows on a steep and well-drained slope in what *Bannister* and *Smiley* [1955] term, in the sense that the word is used in dendrochronology, a 'sensitive' site, that is, one in which the soil moisture is derived directly from local precipitation. The oak and gum, on the other hand, are inhabitants of a 'complacent' site or one in which moisture is available from a porous subsoil as well as from direct precipitation. The area from which these particular oak and gum samples were obtained is one of moderately heavy forestation, and of clayey soil containing a moderate amount of humus. The environment in which the swamp cypress grows is necessarily one of standing swamp water; cypress swamps contain abundant organic remains in various stages of decay.

If it be assumed that ecological conditions are responsible for the differences observed in the extrapolated contemporary assay, then a reasonable mechanism by which these differences are achieved must be postulated. A mechanism which may be called upon to furnish an explanation is that postulated by *Wickman* [1952] in an attempt to explain variations in the abundance of the stable carbon isotopes in plants. According to Wickman's views, old carbon may be introduced into plants either by uptake of carbon dioxide contained in ground water, or by utilization in photosynthesis of carbon dioxide released from the soil. In corroboration of part of Wickman's postulate and of views expressed by *Godwin* [1951], *Deevey* and others [1954] have demonstrated that vegetation growing in hard-water lakes exhibits a decreased radiocarbon content, presumably by introduction into the plant material of inorganic carbon compounds dissolved in the lake water. *Craig* [1954], on various grounds, has rejected as untenable the idea ex-

TABLE 1 – *Radiocarbon assays of woods*

Sample	Radiocarbon assay	
	Actual	Extrapolated to present
	cpm	cpm
Douglas Fir (*Pseudotsuga taxifolia*)		
Western U.S., 15-yr ring	20.20 ± 0.17[a]	20.24 ± 0.17
Same, 225-yr ring	20.43 ± 0.17[a]	21.00 ± 0.17
Oak (Quercus stellata [?]), Cleveland,		
Texas, 0–10-yr rings	19.94 ± 0.17	...
Same, 100-yr ring	20.27 ± 0.17	20.52 ± 0.17
Gum (*Liquidamber styraciflua*) Cleveland,		
Texas, 0–10-yr rings	19.53 ± 0.17	...
Same, 50-yr ring	20.23 ± 0.17[a]	20.36 ± 0.17
Same, 100-yr ring	19.77 ± 0.17	20.02 ± 0.17
Same, 150-yr ring	19.93 ± 0.17	20.31 ± 0.17
Cypress (*Taxodium distichum*) Tangipahoa Parish,		
La., 0–10-yr rings	19.48 ± 0.17	...
Same, 200-yr ring	19.36 ± 0.17	19.86 ± 0.17
Same, 400-yr ring	18.68 ± 0.17	19.68 ± 0.17
Same, 450-yr ring	18.71 ± 0.17	19.84 ± 0.17
Same, 500-yr ring	18.58 ± 0.17	19.85 ± 0.17
Same, 600-yr ring	17.85 ± 0.17	19.35 ± 0.17

[a] Average of two determinations.

TABLE 2 – *Averages of contemporary assay, extrapolated*

Wood	Assay
	cpm
Douglas fir	21.00 ± 0.17
Oak	20.52 ± 0.17
Gum	20.23 ± 0.17
Cypress (*Taxodium*)	19.81 ± 0.17

TABLE 3 – *Extent of dilution exhibited by the various woods*

Wood	Extrapolated contemporary assay	Dilution
	cpm	pct
Douglas fir	21.00 ± 0.17	3.6 ± 1.1
Gum	20.23 ± 0.17	3.3 ± 1.1
Oak	20.52 ± 0.17	2.8 ± 1.1
Cypress	19.81 ± 0.17	1.7 ± 1.2

pressed by Wickman that there can be appreciable cyclic exchange through the atmosphere of carbon dioxide between plants and the pedosphere which would result in enrichment of the plant in C^{12}.

In an effort to shed light on the mechanism which apparently operated in the case of the four woods examined, $C^{12} - C^{13}$ ratios were determined for several of the same wood samples which had been subjected to radiocarbon assay. Results from these determinations indicate that differences among the $C^{12} - C^{13}$ ratios of the various woods are relatively small, and that the measurements do not serve to clarify the mechanism responsible for the variations in radiocarbon content.

Although the evidence is admittedly very scanty, it appears that the difference in extrapolated contemporary assays of the woods may be explained most reasonably by postulating the introduction of relatively small amounts of dead or old carbon into the oak and gum trees, and of a greater amount of old or dead carbon into the cypress tree.

A second feature of interest revealed by the assays of the four woods is that, in every case, the radiocarbon content of the very recent wood was noticeably lower than the radiocarbon content computed by extrapolation to the present of old wood from the same tree. Dilution of atmospheric radiocarbon by ancient carbon introduced by combustion of fossil fuels is thus quite evident.

The extent of dilution exhibited by the Douglas fir, 3.6 pct, is in excellent agreement with the value of 3.5 pct predicted by Harrison Brown (private communication) on the basis of detailed studies of the $C^{12} - C^{13}$ ratio made by Brown's co-workers on rings from the same tree (Table 3).

Quite evident in the foregoing tabulation is a trend of decreasing degree of dilution with decrease in the extrapolated contemporary assay. In spite of the relatively large uncertainties which exist in the estimated percentages of dilution, and in spite of the fact that the number of woods considered is small, the indication that such a trend exists cannot be ignored.

If, as postulated, the difference in the extrapolated contemporary assays are attributable to the incorporation in some of the trees of old carbon, then, by extension, the same posulate may be utilized to furnish a qualitative explanation of the trend of degree of dilution with extrapolated assay. For example, if the cypress utilized a large percentage of carbon older than about 50 years in the synthesis of its woody material, this carbon would not be affected by dilution accompanying the industrial revolution, and the apparent over-all effect due to combustion of fossil fuels would be diminished correspondingly. Although such an explanation may not be adequate to account quantitatively for the results obtained, there apparently exists a connection between the ecology of a tree and the degree of dilution due to the industrial revolution which it exhibits.

As a corollary, it is likely that the most reliable record of the true extent of dilution of atmospheric radiocarbon by carbon from fossil fuels is that furnished by the Douglas fir, the tree which apparently was least affected by assimilation of old carbon. The extent of dilution shown by the Douglas fir is in close accord with the dilution which may be calculated from results reported by *Suess* [1954], but is appreciably higher than his later interpretation [*Suess*, 1955] of less than one per cent.

Evidence on dilution of oceanic carbon—To investigate the possibility that the radiocarbon concentration in shallow oceanic carbonates may have been decreased perceptibly by dilution from dead carbon derived from the burning of fossil fuels, assays were made of the radiocarbon contents of calcareous shells of marine organisms collected in the nineteenth century, and, for comparison, of the radiocarbon contents of their modern counterparts.

Past experience in Humble's laboratories has indicated that modern shells of organisms which grow in restricted bays or estuaries may often have abnormally low radiocarbon concentrations. For this reason, only those historically-dated old marine shells were used which came from open coastal waters. All of the shells were from Atlantic or Caribbean waters.

Through the courtesy of William J. Clench of the Museum of Comparative Zoology, Harvard University, it was possible to obtain an ark shell, collected in South Carolina in 1850 by Louis Agassiz, and an ark shell collected in Jamaica in 1845 by Governor Adams of Jamaica. The Charles-

ton Museum generously contributed a Venus clam collected in 1859 at Sullivan's Island, Georgia, by Edmund Ravenal, and Harry S. Ladd of the U. S. National Museum in Washington graciously gave a *Buccinum* collected in 1873 at Casco Bay, Maine. Table 4 lists the actual radiocarbon contents of the old, historically-dated shells and the corresponding contents after extrapolation to zero age.

For comparison with the Venus clam collected by Ravenal, good values of the radiocarbon assay of the modern counterpart were available. Robert A. Moody, then of Humble's Production Research Division, with the generous cooperation of his father, Clarence L. Moody, had collected a number of genera of living organisms from a variety of environments on the Atlantic coast. Three Venus clams from different environments, collected near Sullivan's Island, the location from which the Ravenal shell came, gave assays of 20.33, 20.39, and 20.24 cmp, each with a statistical uncertainty of ±0.17 cpm. If the average of these, 20.34 ± 0.17 cpm, be used as the representative assay of the modern counterpart, the extent of dilution indicated by the Venus clam is 2.1 ± 1.6 pct.

In the computation of dilution by use of data from the Agassiz and from the Jamaica samples, there is some uncertainty in assigning assays to the respective modern counterparts. No sample of living ark could be obtained from the South Carolina coast, whence the Agassiz sample came, since the Incongruous Ark is now relatively rare on this coast. No modern sample of Cut Ribbed Ark from Jamaica was readily available. Consequently, for comparison with the Agassiz sample, use was made of a sample of *Anadara brasiliana Lamarck* collected at Coronado Beach, Florida, in 1938, and for comparison with the Jamaica sample a shell of *Barbatia candida Helbling* was employed which had been collected at Fort Myers, Florida, in 1921. Both of the latter shells were obtained through the courtesy of William J. Clench.

The assay of the 1938 Coronado Beach ark was 19.52 ± 0.17 cpm, which extrapolates to 19.56 ± 0.17 cpm for zero age before the present. If this value be used as representative of the modern counterpart of the Agassiz sample, the amount of dilution which had taken place to 1938 is indicated to be 3.2 ± 1.6 pct.

The assay of the 1921 *Barbatia candida* from Fort Myers, Florida, was 20.31 ± 0.17 cpm, equivalent to 20.39 ± 0.17 cpm extrapolated to the present. Use of this value for comparison with the Jamaica sample yields an estimated dilution, as of 1921, of negligible percentage.

TABLE 4 – *Radiocarbon contents of historically dated marine shells*

Shell	Actual assay	Assay extrapolated to zero age
	cpm	cpm
Venus clam (*Veneridae Mercenaria*), collected by Ravenal, Sullivan's Island, S. C., 1859	20.54 ± 0.16 20.42 ± 0.16 20.60 ± 0.16	
Av.	20.52 ± 0.16	20.77 ± 0.16
Incongruous Ark (*Anadara brasiliana Lamarck*) collected by Louis Agassiz, South Carolina, 1850	19.95 ± 0.17	20.21 ± 0.17
Cut Ribbed Ark (*Barbatia candida Helbling*) collected by Gov. Adams, Jamaica, 1845	20.18 ± 0.17	20.44 ± 0.17
Buccinum undatum (*L*) collected by U.S. Fish & Wildlife, Casco Bay, Maine, 1873	19.98 ± 0.17	20.11 ± 0.17

Unfortunately, no assay has yet been made of modern *Buccinum* from Casco Bay for comparison with that of the 1873 specimen. A modern sample from Digby Neck, Nova Scotia, has been examined, however, and has given 20.41 ± 0.17 cpm, which is higher than the extrapolated counting rate of the 1873 Casco Bay sample.

In an appraisal of the evidence bearing on dilution of the radiocarbon in these marine shells, most weight should be given to that furnished by the comparison of the results obtained from the Ravenal shell with those obtained from modern Venus clam shells. Slightly less weight should probably be given to the evidence supplied by the Agassiz sample and its Coronado Beach modern counterpart, and, because of the probability of environmental differences, less reliance can be placed on the comparison between the Jamaica and the Fort Myers samples and on the comparison between the Casco Bay and the Digby Neck samples. Such an appraisal leads to the conclusion that marine shells, and hence the dissolved carbonates of shallow oceanic waters, appear to show a perceptible dilution effect. Although the evidence at hand is extremely limited, it indicates that the extent of the dilution may be in the neighborhood of one to two per cent.

Implications of the radiocarbon evidence—From

the radiocarbon evidence on the dilution of atmospheric and oceanic carbon by carbon dioxide from fossil fuels it is possible to estimate the rate at which carbon dioxide enters the oceans, and to deduce some information on the mixing times of the oceans. These topics are considered in the following sections.

Rate of entrance of atmospheric carbon dioxide into the oceans—It has been deduced in a preceding section that the dilution of atmospheric carbon dioxide by fossil carbon dioxide is, at present, likely in the neighborhood of about 3½ pct. If it be assumed that the carbon dioxide introduced into the atmosphere as a result of the industrial revolution is predominately that from fossil fuels (tantamount to the assumption that the amount of 'recent' carbon dioxide resulting from agricultural activity is small in comparison), then the increase in mass of atmospheric carbon dioxide is correspondingly about 3½ pct.

In order that the rate of exchange of carbon dioxide between atmosphere and ocean may be estimated, it is desirable to postulate that (1) the entrance rate of carbon dioxide into the ocean is proportional to the mass of carbon dioxide in the atmosphere, and (2) the exit rate of carbon dioxide from the ocean to the atmosphere is constant, since it may be assumed that no appreciable change in carbon dioxide concentration in the upper part of the ocean results from the addition of the fossil carbon.

By utilization of an approximate expression for the rate of production of carbon dioxide shown in Figure 1, the rate of change of carbon dioxide in the atmosphere is given by

$$\frac{dM_a}{dt} = Bke^{kt} - \alpha M_a + \beta \qquad (1)$$

where

M_a = mass of carbon dioxide in the atmosphere
t = time
Bke^{kt} = rate of production of carbon dioxide by combustion of fossil fuel, as derived from the curve $B(e^{kt} - 1)$ fitted to Fig. 1
α = entrance coefficient
β = exit rate

The solution, on integration of (1), is

$$M_a = M_{a|t=0} + \frac{Bk}{k + \alpha}\left[e^{kt} - e^{-\alpha t}\right] \qquad (2)$$

In this solution, $t = 0$ at the year 1860.

Solution of (2), utilizing the estimated increase of 3½ pct for the mass of carbon dioxide in the atmosphere, yields a value for a of 0.062 per year. This is the fractional part of the atmospheric carbon dioxide which enters into the ocean each year.

In comparison, *Suess* [1953] has given a value, which may be considered as comparable, of from 0.02 to 0.05. Expression of an entrance coefficient given by *Dorsey* [1940, pp. 552–553], determined in the laboratory for carbon dioxide and pure water, in terms similar to those above yields a value of 0.044.

Mixing times of the oceans—From the evidence on dilution of oceanic carbonates, the information on rate of exchange of carbon dioxide between atmosphere and ocean, and an estimation of the ratio of radiocarbon concentration in the ocean to that in the atmosphere, it is possible to draw rough conclusions as to the rate of mixing in the oceans. For this purpose, it is necessary to formulate a simplified model representative of the atmosphere-ocean system which embodies, in a broad sense, the major physical factors involved, yet which is amenable to analytical treatment.

A convenient model embodying the atmosphere, an upper ocean, and a deep ocean, is illustrated schematically in Figure 2. In this model, it may be assumed that (1) the mixing of carbon dioxide in the atmosphere is rapid, and the concentration of radiocarbon is uniform, and (2) the mixing of carbon dioxide (and carbonates) in the upper ocean is rapid, and the concentration of radiocarbon is uniform.

With these assumptions, the radiocarbon distribution in the model can be described by

$$\alpha M_a q_a + \eta q_d - \alpha M_a q_o - \eta q_o - \lambda q_o M_o = 0 \qquad (3)$$

$$\eta q_o - \eta q_d - \lambda q_d' M_d = 0 \qquad (4)$$

where

α = entrance coefficient of carbon dioxide into the ocean
M_a = mass of carbon dioxide in the atmosphere
q_a = concentration of radiocarbon in atmospheric carbon dioxide
η = rate at which carbon dioxide components are transferred out of the upper ocean into the deep ocean
q_d = average concentration of radiocarbon in carbon dioxide components returned from the deep ocean to the upper ocean
q_o = concentration of radiocarbon in the carbon dioxide components of the upper ocean
M_o = mass of the carbon dioxide components of the upper ocean
λ = decay constant of radiocarbon
q_d' = average concentration of radiocarbon in the carbon dioxide components of the deep ocean
M_d = mass of the carbon dioxide components of the deep ocean.

Simultaneous solution of (3) and (4) yields

$$\frac{q_d'}{q_o} = \left[\left(\frac{q_a}{q_o} - 1\right) - \frac{\lambda M_a}{\alpha M_a}\right]\frac{\alpha M_a}{\lambda M_d} \tag{5}$$

Introduction of

$$a = \frac{q_a}{q_o} - 1 \tag{6}$$

gives

$$\frac{q_d'}{q_o} = a\frac{\alpha M_a}{\lambda M_d} - \frac{M_o}{M_d} \tag{7}$$

To evaluate the transit time of the carbon dioxide components through the deep ocean in terms of the average concentration of radiocarbon as given in (7), it is necessary to postulate a mechanism for the transfer. If it be assumed that the transfer is as that through a uniform pipe, then it is easily shown that

$$\frac{q_d'}{q_o} = \frac{1 - e^{-\lambda T}}{\lambda T} \tag{8}$$

where T = transit time through the pipe.

Combining (7) and (8) permits calculation of the transit time if values can be assigned to the quantities a, M_o, M_a, and α.

A value for a may be obtained by assuming that a radiocarbon fractionation of five per cent occurs in photosynthesis, and by use of extrapolated values of radiocarbon assays of historically-dated shell and wood samples. Values of M_a may be obtained by use of estimates of the dilution of radiocarbon in near-surface oceanic carbonates and in atmospheric carbon dioxide, and by consideration of the total masses of carbon dioxide in the atmosphere and in the ocean. In the estimation of the masses of carbon dioxide in the atmosphere and in the ocean, several sources of data were considered. The values chosen for carbon dioxide contents were

$$M_a = 2.4 \times 10^{18} \text{ gms.}$$

$$M_o + M_d = 1.4 \times 10^{20} \text{ gms.}$$

The value of α has been estimated in a preceding section. Use of these quantities in (7) and (8) yields the results shown in Table 5.

In this tabulation, the thickness of the upper ocean was computed from $\frac{M_o}{M_o + M_d}$ and from data on depth and volume of the oceans given by *Sverdrup* and others [1942].

In the particular model used, the value of the transit time, or turnover time, is strongly dependent on the values chosen for α and for a. These, in turn, depend strongly on the values used for the extent of dilution, for the extrapolated contemporary assays of woods and of shells, and for the isotopic fractionation of radiocarbon. An increase either in α or in a leads to a smaller transit time.

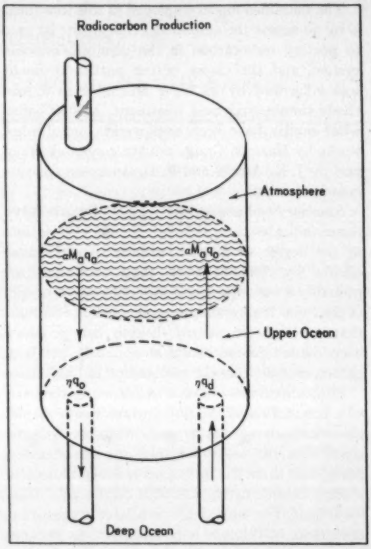

FIG. 2 — Model used for distribution of radiocarbon

TABLE 5 – *Results of computations*

Dilution of upper oceanic carbonates by carbon from fossil fuels	T	$\frac{M_o}{M_o + M_d}$	Thickness of upper ocean	Apparent age of carbon in upper ocean
pct	years		m	years
1	3200	0.22	800	620
1½	5100	0.16	600	580
2	7200	0.11	400	540

The transit times listed in the above table have been criticized by Roger Revelle (private communication) as being too great, on the ground that they are not consistent with estimates of turnover time made by use of data on heat flux through the ocean floor. In view of the crudeness of the model utilized, the assumptions employed, and the uncertainties in various of the values which were used, the results, quantitatively, are certainly open to question.

The simplified model employed in this treatment is by no means the only model that might be used to portray radiocarbon in the atmosphere-ocean system, and the choice of the particular model was influenced by its being amenable to a relatively simple analytical treatment. Models somewhat similar have been employed in unpublished works by Harmon Craig (private communication) and by J. R. Arnold and E. C. Anderson (private communication).

Summary and conclusions—The radiocarbon evidence indicates that, although there are variations in the degree of dilution with fossil carbon exhibited by different trees, these variations are probably a consequence of differences in ecologies of the trees. If allowance be made for this, it follows that atmospheric carbon dioxide has probably been diluted to the extent of about $3\frac{1}{2}$ pct with carbon dioxide from the combustion of fossil fuels.

The radiocarbon evidence indicates, on the basis of a comparison of the radiocarbon assays of old, historically dated marine shells from the Atlantic coast with the assays of their modern counterparts, that there has been a perceptible dilution of shallow oceanic carbonates with dead carbon from fossil fuels. The limited data available suggest that the extent of dilution is possibly one to two per cent.

Of interest in connection with the distribution of radiocarbon in the carbon cycle are (1) the rate of exchange of carbon dioxide between the atmosphere and the ocean, and (2) the rate of turnover of carbonates in the ocean. The use of simplified mathematical models and of assays of historically dated shell and wood samples allows an estimate to be made of the rate of exchange and turnover time. The limited experimental data available suggest a turnover time of a few thousand years and an exchange rate of about $\frac{1}{16}$ of the atmosphere per year. It may further be deduced that the thickness of the upper ocean, assumed to be thoroughly mixed, is a few hundred meters and that the apparent age of the carbon in the upper ocean is about 600 years.

The apparent age of about 600 years for the upper ocean is a consequence of return of old carbon from the deep ocean; in some shallow seas, where the rate of exchange with the atmosphere may be the governing factor, it may be expected that the apparent age will be much less. As a corollary, it is likely that significant variations will be found in the radiocarbon contents of marine shells from areas which participate to varying extents in the interchange of waters with the deep oceans.

Most of the conclusions reached in this work must necessarily be considered as tentative, and more data are required to substantiate, modify, or refute them. Many points remain obscure, and they can be elucidated only by bringing to bear on them new evidence from additional data.

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Surveying by Occultations

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Abstract—A method of surveying which uses data obtained from photoelectrically observed occultations is described. The method is applicable in those cases where it is desired to connect triangulation systems which are too widely separated to be tied together by the usual means. The discussion includes the prediction and reduction of occultations. From the reduction of one occultation observed by teams in different geodetic systems, a line of position is obtained. A second similarly observed occultation yields a second line of position and hence a fix.

Introduction—In January, 1955, the U. S. Army Map Service, at the request of the U. S. Coast Guard, inaugurated a program of surveying by occultations between the Philippine Islands and the so-called Marianas chain, including the Mariana and Caroline Islands. At the time the request was made, it was known that the geodetic positions of the Caroline and of the Mariana Islands were incorrect by perhaps as much as ±2000 m in latitude and longitude. It was deemed necessary for navigational purposes to correct the positions of the islands so that the probable error of their coordinates would not exceed ±300 m in both latitude and longitude.

Because the distances between the geodetic systems ranged from approximately 500 mi, at their closest approach (with nothing but the Pacific ocean in between), to 1600 mi, at their farthest, the photoelectric method of occultation observations was chosen as the only one practicable to attempt a tie between the two systems. In this method, the instruments used are the Brush Model 202 oscillograph combined with the Brush Model 932 amplifier, both of which are attached to a 12-inch Cassegrainian telescope behind whose focal point a 1P21 RCA phototube is placed. The data are recorded on a double channel paper tape. In one channel there is a recording of the light intensity of the star involved in the occultation while in the other channel there are usually WWV or WWVH time signals (Fig. 1).

Theory—The theory behind the method, first expounded by Bessel, is as follows. If we imagine the Moon to pass between an observer on the Earth and a star, a shadow of the Moon can be visualized as thrown into space and intersected by the Earth (Fig. 2). As the Moon revolves eastwards around the Earth this shadow traces a path across the Earth. From any point within this path, the star will be occulted. If we concern ourselves with one specific observer, he will see the occultation occur at a particular point on the Moon's edge. This particular point can then be imagined as tracing a line on the Earth such that every observer on that line would notice the occultation of this star occurring at the same point on the Moon's limb. This line is defined as an equal-limb line. The effect of the Moon's motions during the interval of time that it takes one point on its shadow's edge to pass eastwards between two specific observers can be computed and allowed for. Knowing the angular rate of revolution of the Moon around the Earth and the rate of rotation of the Earth combined with a knowledge of the size of the equatorial radius of the Earth and the parallax of the Moon reduces the problem to one of knowing the velocity and time, and computing the distance.

The method of predicting an occultation of the type discussed in this paper has been incompletely described elsewhere [*O'Keefe*, and *Anderson*, 1952]. It may suffice to give a résumé here. Let us first imagine a plane passing through the center of the Earth and perpendicular to a line from the star through the center of the Moon. This plane, known as the fundamental plane, then becomes a convenient device to use in the calculations pertaining to an occultation. Now imagine that instead of observing an occultation from the Earth looking outward at the sky, we place ourselves at the star and observe all the phenomena of the occultation as taking place upon the fundamental plane. This means that we have to project the observer's position on the Earth perpendicularly downward to the fundamental plane and also let the shadow of the Moon intersect it.

We now set up a system of rectangular coordinates whose common origin is the center of the Earth. The y axis lies in the fundamental plane and is directed positively through the north. The z axis is perpendicular to the fundamental plane and is positive in the direction of the star. The x axis is the line of intersection of the fundamental plane with the plane of the Earth's equa-

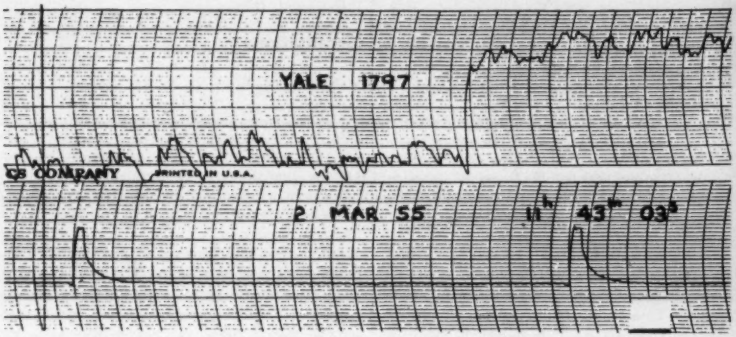

FIG. 1 – Photoelectric recording of an occultation; in the upper channel is a recording of a star's light during an immersion; the sharp change in intensity indicates the instant at which the star was occulted by the Moon; the oscillations recorded after the moment of the occultation are due mainly to background light of the Moon; the lower channel has recorded in it the time ticks, one second apart in time; in practice, the tape runs through the oscillograph at a speed of 125 mm/sec; the instant of the occultation can be easily measured to 0.010 sec; the earlier time is at the left.

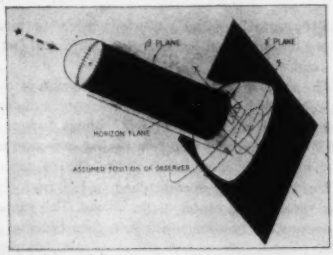

FIG. 2 – Shadow cylinder representing local circumstances of an immersion; the dark cylinder is the shadow cast by the Moon as it blocks the star light; tangent to the cylinder at the position angle of the occultation is the β plane; on the Earth's surface, through the assumed position of the observer, a local coordinate system of eastings and northings has been drawn; the reduction determines the points on the easting and northing axes at which the β plane intersects these axes; in a short distance on the Earth, the β plane can be imagined as coincident with the limb of the moon in the vicinity of the observer; since at the instant of occultation the observer is located on the projected limb of the Moon, the reduction supplies the equivalent of a line of position; through the assumed position of the observer is drawn the γ plane, parallel to the fundamental plane; also drawn through the same point is the observer's horizon plane, both of which are used in the reduction.

tor. The x axis is positive toward the east, as seen from the star, in order to yield a right-handed coordinate system.

We are interested in arranging matters so that the occultation will occur at the same point on the Moon at two separate sites. One site is chosen as the origin from which to run the line. We usually select as our origin a point within the smaller of the two systems between which we are attempting to establish a better relation. This provides a much greater probability that the equal-limb line will pass somewhere through the larger geodetic system.

Prediction—The first step involved is the computation of the time and the position angle on the Moon. The position of the projection of the star on the fundamental plane relative to the projection of the Moon's center on the same plane is

$$\chi = 180° + \tan^{-1}\left(\frac{x - \xi}{y - \eta}\right) \qquad (1)$$

$$x = a\,\frac{\sin(\alpha_{(} - \alpha_{\odot})\cos\delta_{(}}{\sin\pi_{(}}$$

$$\xi = a\,\rho\cos\phi'\sin h$$

$$y = a\,\frac{\cos\delta_{\odot}\sin\delta_{(} - \cos(\alpha_{\odot} - \alpha_{(})\sin\delta_{\odot}\cos\delta_{(}}{\sin\pi_{(}}$$

$$\eta = a\,[\rho\sin\phi'\cos\delta_{\odot} - \rho\cos\phi'\sin\delta_{\odot}\cos h]$$

x, y = coordinates of center of Moon on fundamental plane

ξ, η = coordinates of observer on fundamental plane

α_ℓ, α_* = right ascensions of Moon and star, respectively

δ_ℓ, δ_* = declinations of Moon and star, respectively

π_ℓ = equatorial horizontal parallax of Moon

a = Hayford equatorial radius, meters

$\rho \sin \phi'$, $\rho \cos \phi'$ = functions of observer's latitude which have been corrected for the effects of refraction, elevation, spheroid, and geoid

h = local hour angle of star

This relation holds at the Universal Time when the observer's position as projected onto the fundamental plane is at a distance from the projected center of the Moon equal to the radius σ, or when

$$(x - \xi)^2 + (y - \eta)^2 = \sigma^2 \tag{2}$$

For prediction purposes, σ is usually taken as

$$\sigma = 0.27248070a \tag{3}$$

In all the prediction computations the Hayford spheroid is the one used to represent the Earth.

The next step is the selection of the geographic coordinates of the second site and the time of the occultation as observed there. This is usually accomplished as follows: For several different times geographic coordinates of sites, in the vicinity of the site to be chosen from which the occultation would be seen to occur at the same point on the Moon, are computed. These sites are then plotted on a large-scale map and a smooth line drawn through them. A point on this line in a suitable location is then selected as the second site from which to observe the occultation. The formulas used to determine the geographic coordinates are the following

$$\lambda = H' + t_0 - h \tag{4}$$

where

$$H' = STO^h - \alpha_*$$

$$h = \sin^{-1}(\xi / \cos \phi_1)$$

$$t_0 = 15.04106864\ (T + t)$$

STO^h = sidereal time at 0h 00m Universal Time (UT), and

15.04106864 = sidereal equivalent of one hour mean solar time in degrees.

$$\phi = \tan^{-1}\left(\frac{\sin \phi_1}{\cos \phi_1 \sqrt{1 - e^2}}\right) \tag{5}$$

where

ϕ_1 = parametric latitude

$$\sin \phi_1 = \eta_1 \cos d_1 + \zeta_1 \sin d_1$$

$$\eta_1 = 0.27248070\ (a \cos \chi + y)/\rho_1$$

$$\zeta_1 = \sqrt{1 - \xi^2 - \eta_1^2}$$

$$\rho_1 = \sqrt{1 - e^2 \cos^2 \delta_*}$$

$$\tan d_1 = \frac{\tan \delta_*}{\sqrt{1 - e^2}}$$

e = eccentricity of Hayford spheroid

This concept was developed in a series of lectures delivered at the U. S. Coast & Geodetic Survey in 1948 by W. D. Lambert.

After the time and position angle have been initially computed for the second site, several elevation corrections are applied to the coordinates of the second site, which correct them for the effects of refraction, elevation above mean sea level, height of the Hayford spheroid above reference ellipsoid of the particular datum point, and for elevation of geoid.

The computations leading to a first choice for a second site neglected the refractive effect of the Earth's atmosphere. As a result, geographic coordinates are found for which the occultation would not be seen at the computed altitude, hour angle, and position angle. A correction is therefore applied to the coordinates to obtain a site from which the occultation would be seen at the computed values of altitude, hour angle, and position angle. After the occultation has been successfully observed at each end of the line a reduction is performed.

Reduction—The first step in the reduction is the measuring of the tapes to determine the true time of the occultation at each site. Corrections to the recorded time such as transmission time, WWV or WWVH corrections as announced in the *Naval Observatory Monthly Time Bulletins* to convert the signals to the UT2 time system, and instrumental corrections are taken account of as described by *O'Keefe* and *Anderson* [1952].

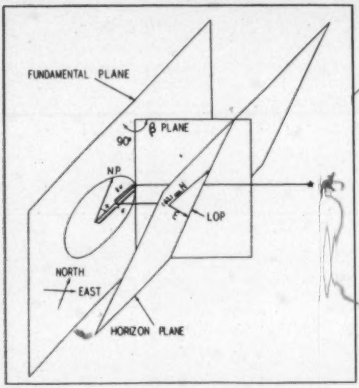

FIG. 3 – Planes involved in reduction; this figure illustrates three of the principal planes involved in the reduction process and their relationship to each other during one particular occultation; tangent to the projected image of the Moon on the fundamental plane at the position angle χ is the β plane; the value of $\Delta\sigma$ is equal to the difference found between the values of σ determined at the known and unknown sites.

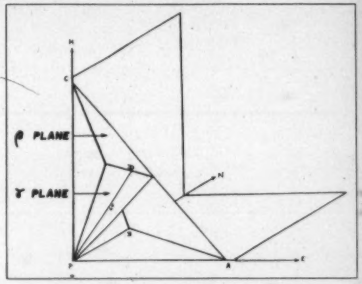

FIG. 4 – γ plane in reduction; in the reduction process, the γ plane is drawn through the assumed position of the observer P, and parallel to the fundamental plane; the perpendicular distance in this plane from the observer to the β plane is $\Delta\sigma$; the local coordinate system is defined by the axes E, N, and H, while the axes E and N define the horizon plane; knowing the direction cosines of the various axes with respect to each other, values of the easting and northing, PA and PB respectively, are computed; the line BA is a segment of the line of position as determined from the reduction.

As stated in the introduction, what we are trying to do is to correct the position of the unknown site. This can be accomplished by successfully observing at least two occultations from the one unknown site to any two places in the known geodetic system. Each successfully observed pair of occultations results in the obtaining of the equivalent of one line of position at the unknown site. Hence two or more favorable pairs of occultations results in a fix.

In regard to the known site, we assume that its position is known with respect to the center of the Earth and to the polar axis of the Earth. In the prediction computations, a mean radius of the Moon has been used. Since the observed value of the lunar radius is the crux of the reduction theory, it may be well to say a few words about it now.

Because of the mountainous character of the Moon and the irregular edge that it presents as a result, the radius of the visible Moon varies all around its perimeter.

Each favorably observed occultation provides an equation for each site of the form

$$\sigma^2 = (\xi - x)^2 + (\eta - y)^2 \qquad (6)$$

At the known site we may assume that ξ and η are known; x and y, the Moon's coordinates on the fundamental plane, may be slightly in error, but the error will be the same, for all practical purposes, at each end of the line.

If the geographical coordinates at the unknown site were correct (as are those of the known site), the σ obtained there would be equal to that obtained at the known site. However, this seldom occurs, and we can blame the discrepancy on the incorrectness of the latitude and longitude adopted for the unknown site. Since the astronomical errors have the same value at each end of the equal-limb line, subtracting σ (unknown) from σ (known) leaves us with the error $\Delta\sigma$ caused solely by the error in latitude and longitude.

As a result, the observations at the known site are used in effect to correct the astronomical data to get an observed radius of the Moon at the point on the limb where the occultation occurs. It is well understood, of course, that the observed radius is in part a fiction; it absorbs not only genuine corrections to the Moon's radius but also the radial component (at the given position angle) of the error in the Moon's position. Since each pair of observations are made at the same point on the Moon's limb, and since only the radial component affects the time of occultation, this device is justified.

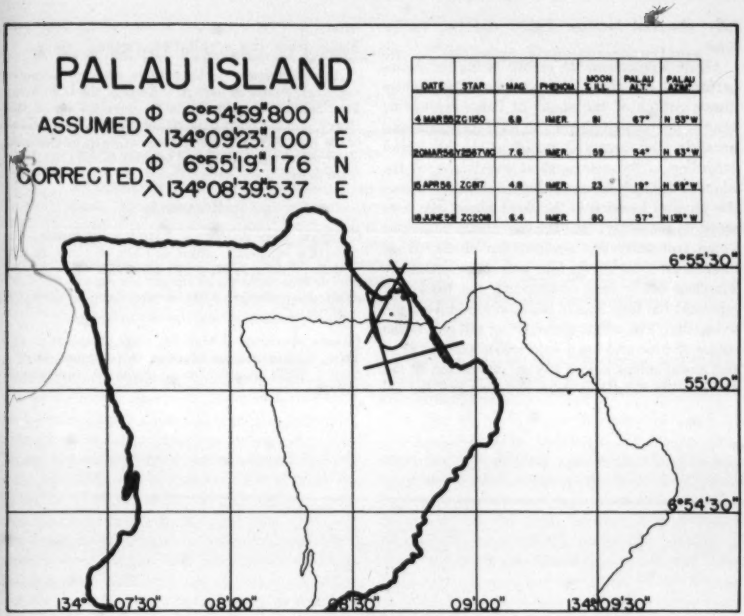

FIG. 5 – Palau Island reduction

It was previously stated that one pair of successful occultations yields a line of position at the unknown site. This may be obtained in the following manner through the use of eastings and northings. At the unknown point of observation, a local coordinate system is set up with an E axis running east and west, an N axis running north and south, and a third, or H axis, extending vertically upward.

As the Moon's cylindrical shadow sweeps across the site, we can imagine the leading or following surface of the cylinder to be replaced by a plane β tangent to the cylinder along the line through the observer. If, at the observed time of occultation, we can determine the intercepts of this plane on the E and N axes of the local coordinate system, we then have a line of position for the observer (Fig. 3).

Through the assumed position of the observer we construct a plane γ parallel to the fundamental plane. The perpendicular distance in the γ plane from the observer P to the β plane is evidently $\Delta\sigma$ (Fig. 4).

Using this value of $\Delta\sigma$ and a set of direction cosines, we can then determine the values of the intercepts of the β plane on the easting and northing axes of the local coordinate system of the observer from the expressions

$$E = \frac{\Delta\sigma}{C_{11} \sin \chi + C_{21} \cos \chi} \tag{7}$$

$$N = \frac{\Delta\sigma}{C_{12} \sin \chi + C_{22} \cos \chi} \tag{8}$$

where the C_{ij} are the direction cosines of the fundamental plane axes with respect to the local system axes [*O'Keefe* and *Anderson*, 1952].

Results—Occultation campaigns were conducted during the first halves of 1955 and 1956 between the Philippines and the Caroline Islands. A total of four pairs of occultations were success-

fully observed between Palau and the Philippines.

Figure 5 represents the results of the reductions performed on these observations. The lightly drawn outline of the island of Palau represents, against the background of the fixed meridians and parallels, the accepted position of the island according to the astronomical coordinates of the island. The black dot on the light outline represents the physical location of the fixed pier of the telescope on the island. The heavily drawn outline of Palau represents the new position of the island found from reducing the four pairs of occultations. The four black lines surrounding the fixed pier represent the four lines of position found from the reductions. The ellipse surrounding the pier is the ellipse of error and has a semi-major axis of 252 m and a semi-minor axis of 138 m. At the top of the diagram are listed the stars observed and the assumed and corrected coordinates of the fixed pier found from the occultation method.

Acknowledgements—The authors wish to acknowledge their thanks to John A. O'Keefe of the U. S. Army Map Service for guidance in the development of this theory, and to Robert Bennett and his Geodesy Division of the Map Service, Army Forces Far East, for checking our prediction equations and bringing to our attention a slight error.

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A Note on the Precision of Estimation of Missing Precipitation Data

JAMES E. McDONALD

Abstract—Climatological studies in which early precipitation records are used frequently lead to the necessity of estimating missing data. The present note summarizes a small series of tests of one objective estimation scheme identical in form to the normal-ratio method of Paulhus and Kohler but applied here to missing seasonal totals rather than to missing storm totals. The results suggest that estimation errors in the neighborhood of 25 pct must be expected in estimating seasonal totals using two index stations under conditions typical of those forced upon the investigator dealing with older records. Increasing the number of index stations beyond two does not seem warranted. Errors of 25 pct in seasonal totals, though not negligible, are small enough compared to coefficients of variation typical of seasonal totals of precipitation in the drier portions of the United States, that the use of such a method in climatic studies is desirable.

Introduction—In many meteorological and hydrologic investigations, it becomes necessary to use precipitation records which contain intermittent breaks due to change of observing personnel, absence of observer from his station, etc. Such breaks are, unfortunately, fairly frequent in older (say pre-1920) records from Weather Bureau cooperative observers whose unpaid services could not always be obtained entirely continuously, and the result is that the user of such data must either exclude from analysis those periods of record containing gaps, or else find an objective estimation scheme for filling the gaps. Although it would be difficult to defend with quantitative arguments the view that any sort of reasonable objective estimate is preferable to an isolated gap, this is in fact the writer's view. It becomes especially desirable to fill such gaps with systematic estimates in investigations where automatic analysis equipment is being used to process punchcard data, for programming such equipment to enable it to accept gaps is usually quite inconvenient.

In the cases where the investigator has available the original daily records, the problem of missing monthly or seasonal totals can be solved by estimating those particular daily precipitation amounts whose absence from the original records creates the missing monthly total. A rather extensive study of this problem has been conducted by *Paulhus* and *Kohler* [1952] in the context in which this problem arises in current processing of climatological data by the U. S. Weather Bureau. However, if one does not have original daily records available, as is most commonly the case, then a distinct question, not answered by the results of those investigators, arises. One may prefer to fill gaps in the monthly, seasonal, or annual records for stations by some objective scheme that entails use of no more detailed data than the widely available monthly totals.

In the U. S. Weather Bureau–University of Arizona cooperative punchcard climatology program just this problem arose with regard to seasonal precipitation totals missing from non-Arizona records whose originals were unavailable. To shed some light on the order of magnitude of errors incurred by one specific estimation scheme, a small synthetic experiment was conducted. The results are summarized here since, though limited in scope, they give a useful indication of the error level for an estimation problem not treated elsewhere in the literature, to the knowledge of the writer.

Estimation equation—The estimation scheme that has been tested and used in the University of Arizona precipitation studies is identical in form with that termed the 'normal-ratio method' by Paulhus and Kohler. It is best described in symbolic form as follows: Denote by P_{ik} the precipitation reported for the ith time-period (for example, the ith day of a month, ith month of a year, etc.) at the kth station of a group of climatological stations in a given area, and let $\overline{P}_{ik}$ be the mean value for that kth station and ith time-period over a specified long period of years. (Thus, if one were dealing with monthly totals, $i = 3$ might specify March, and $\overline{P}_{3k}$ would be the long-term mean March precipitation at the kth station.) If the jth station has no report for the ith period, then an estimate of this missing datum, denoted by (P_{ij}), is given by

$$(P_{ij}) = (1/n) \sum_{k=1}^{n} \frac{\overline{P}_{ij}}{\overline{P}_{ik}} \cdot P_{ik} \qquad (1)$$

where the sum over k from 1 to n and division of the right member by n implies that one uses as the final estimate an average of n individual estimates derived from actually reported values at n stations located near the jth station. Paulhus and Kohler have referred to the station whose missing datum is to be estimated as the 'interpolation station,' while the several stations whose data are employed to carry out the estimate are termed by them 'index stations.' It seems desirable to adopt their terminology here.

Discussion of estimation scheme—The following general comments about the scheme of (1) may be made:

(a) This scheme would seem, on general principles, to be superior to any that gave (P_{ij}) as some function of only the concurrently reported values, P_{ik}, for (1) weights the estimate in proportion to the ratio of the long-term means at the jth and kth stations, and in actual practice one usually has to deal with station-pairs involving unequal means. The scheme of (1) is, at the same time, clearly superior to mere insertion of $\overline{P}_{ij}$ as a crude estimate of (P_{ij}), for (1) allows any anomalous characteristics of the precipitation peculiar to the particular ith time-period in question to enter through the P_{ik}. Briefly, (1) gives weight both to long-term climatic relationships between the interpolation station (jth station) and the index stations and also to the departures from normal characterizing the ith period (as revealed by the departure from unity in the n ratios, $P_{ik}/\overline{P}_{ik}$), that appear as factors in the n terms of the sum on the right of (1). *Paulhus* and *Kohler* [1952] have shown, in fact, that this normal-ratio method gives substantially more reliable estimates of missing short-term precipitation amounts (missing days or storm-totals) than a simple scheme based just on current totals at nearby stations, and reference should be made to their paper for additional arguments in favor of a normal-ratio approach.

(b) The scheme symbolized by (1) tacitly assumes that ratios of precipitations rather than sums or differences should be used in estimating missing data. This general point is discussed by *Conrad* and *Pollack* [1950, pp. 235–237], who conclude that in the case of precipitation data, it is the ratio and not the difference of two stations' receipts that are quasi-constant. Their conclusion rests, apparently, only on empirical evidence and such evidence is not elaborated by those authors. One might question the generality of the ratio-assumption on the grounds that inter-station precipitation regression equations frequently contain non-zero intercepts whose magnitude is sometimes so great as to seemingly vitiate the ratio method. However, this difficulty must, in almost all cases, become unimportant when the n index stations are all chosen from the immediate geographic (climatographic) vicinity of the interpolation station, for then the several regressions of the jth on the kth stations can reasonably be expected to exhibit zero or nearly zero intercepts.

(c) It is quite essential that all of the means, $\overline{P}_{ij}$ and $\overline{P}_{ik}$, be means computed for the same period of years, for otherwise secular trends in precipitation can very easily introduce systematic error into the estimation.

(d) If any information exists as to patterns of correlation between the interpolation station and surrounding index stations, it is obvious that one should select the index stations from regions of maximum correlation to optimize the estimate in (1), but lacking such information, proximity and topographic factors must serve as deciding considerations. In the program with which the writer is associated, only the latter have been used thus far, for reasons of present lack of detailed information concerning correlation patterns.

After having studied the efficacy of the estimation scheme of (1) it was found that essentially this same scheme has been discussed earlier by *Keeler* [1944], who tried several elaborations of this scheme, including one in which weighting coefficients dependent on the azimuthal distribution of the index stations were employed in making the estimate. Keeler gives no figures indicating comparative precisions of the several elaborations he tried, but states that he finally abandoned them in favor of the kind of scheme given here as (1). He tried values of n from one to five and states that three or more index stations are desirable, but gives no quantitative evidence of comparative performance of the scheme for various n-values. He suggests that the number of years of record entering into the precipitation means employed in the estimates should be "five years or more, if possible," which seems to the writer to be unwarrantedly optimistic. Keeler does not stress the importance of having the means appearing, respectively, in numerator and denominator of the right member of (1) pertain to the same time-periods, yet secular trend effects can, above all with such short averaging periods as accepted by Keeler, lead to quite serious errors of estimate. It bears emphasis that in the arid Southwest (and in similar regions of the world), variability of precipitation is so great that a mere five-year mean can be quite

non-representative. Indeed, a study made by the writer of selected Arizona long-record stations revealed that the 95 pct confidence half-widths of seasonal means of precipitation were about ten per cent of the means, even for stations with records of up to 80 years, and rose to about 20 pct of the mean for records as short as 20 years. Consequently, unless the inherent relative errors of the estimation scheme itself should prove to be much larger than 20 pct, one ought not be satisfied with means based on much less than 20 years, and these should be the means for the same 20 years for the station whose missing datum is to be estimated and for the index stations.

Test of reliability of estimation scheme—As noted above, there are no data in the literature that provide a quantitative evaluation of the error level to be expected for missing seasonal values interpolated by the use of (1), so a simulated run was carried out, 'estimating' winter and summer seasonal totals for two Arizona stations, Tucson and Natural Bridge, for all years from 1900 to 1929, using a variety of predictor-station combinations.

For the purposes of the test of (1), four index stations were chosen for use in a series of synthetic estimates for Tucson, and four for the estimates for Natural Bridge.

These stations, and their airline distances from the two interpolation stations (Tucson and Natural Bridge) are as follows:

Tucson predictors: Oracle, 30 miles north-northeast; Benson, 45 mi east-southeast; Phoenix, 110 mi northwest; Bisbee, 85 mi southeast.

Natural Bridge predictors: Prescott, 60 mi west; Flagstaff, 60 mi north-northwest; Ft. Apache, 95 mi east-southeast (the 1931–52 mean used in the Ft. Apache estimations was that for Whiteriver, about five miles north of Ft. Apache); Phoenix, 70 mi south-southwest.

Previously, as part of another study, double-mass plots of the long-term precipitation records of Tucson and Natural Bridge had been made to determine whether any significant breaks occurred in the histories of these two stations. These double-mass plots are not reproduced here but are presented elsewhere [*McDonald*, 1956], and show that both records are free from discontinuities of magnitude that would vitiate their use in the present tests.

It may be questioned why the test was applied to index stations as far away as 110 miles when there are somewhat closer predictor stations that would surely be preferred in the actual applications of (1). The answer is twofold: First, it was desired to approximate the least favorable rather than the most favorable situations actually encountered, and second, it was desired to apply the test using recent mean ratios in combination with old reports, since this is the most frequent case encountered in practice. Specifically, in the current studies being conducted by the Institute of Atmospheric Physics, we have had to do the largest amount of estimation of missing data for periods before about 1920. But since the two means appearing in the right member of (1) must be means for exactly the same period (or at least for periods which are so nearly identical as to rule out distorting effects of secular trends), it becomes almost indispensable to use in the right side of (1) means over some recent period, common to all record-spans.

Availability of the recently published *Supplements* by the *U.S. Weather Bureau* [1955] has made it an obvious choice to use, throughout all our estimation work, the 22-year means for 1931–52. These 1931–52 means were therefore employed in the synthetic test, but were used to 'estimate' Tucson and Natural Bridge data for the 30-year period 1900–29 as a fairly realistic test of the practical case where gaps in old records are to be filled using means for a more recent period.

Estimates were made for values of n equal to 1, 2, and 4 in (1) in order to gain some notion of how much increase in accuracy might be expected to result from variations in n. Because of gaps in the 1900–1929 records for the four predictor stations, it was not possible to obtain 30 estimates in each case, so for uniformity, the first twenty estimates available, beginning with 1900 were used to evaluate the average error for the present purposes.

The precision of the estimation scheme might be measured in any of a number of ways, of which that chosen for use here was the computation of the average of the absolute values of the errors of 20 pct in each predictor season category. Use of the errors rather than their squares seems desirable since an occasional highly erratic prediction is weighted by a squaring process in an undue proportion for its seriousness. Use of averages of percentages is generally undesirable, and employment of logarithms of relative errors would have been somewhat better here; but since the individual percentage errors did not vary over an extremely large range, a simple average of percentages was felt to provide a fairly adequate

TABLE 1 – *Mean errors of estimation of missing precipitation data*

Predictor stations	Mean error of estimate for Tucson[a]		Predictor stations	Mean error of estimate for Natural Bridge	
	W[b]	S[b]		W[b]	S[b]
	pct	pct		pct	pct
Oracle	23	45	Prescott	22	23
Benson	29	28	Flagstaff	43	35
Bisbee	21	16	Ft. Apache	25	27
Phoenix	26	36	Phoenix	18	34
Oracle, Benson	18	25	Prescott, Flagstaff	31	27
Phoenix, Bisbee	19	23	Ft. Apache, Phoenix	17	27
Oracle, Benson, Phoenix, Bisbee	18	20	Prescott, Flagstaff, Ft. Apache, Phoenix	20	21

[a] Tabular values are means of absolute values of twenty percentage-errors of estimate.

[b] Winter (W) is here the six-month period from Nov. 1 to April 30; summer (S) is the remainder of the year.

TABLE 2 – *Distribution of signs of errors of estimation*

Predictor stations	Per cent of Tucson errors with positive signs		Predictor stations	Per cent of Natural Bridge errors with positive signs	
	W[a]	S[a]		W[a]	S[a]
Oracle	50	44	Prescott	63	59
Benson	32	36	Flagstaff	67	60
Bisbee	59	52	Ft. Apache	41	29
Phoenix	30	37	Phoenix	30	30
Oracle, Benson	32	35	Prescott, Flagstaff	66	62
Phoenix, Bisbee	37	59	Ft. Apache, Phoenix	30	29
Oracle, Benson, Phoenix, Bisbee	35	45	Prescott, Flagstaff, Ft. Apache, Phoenix	54	41

[a] See footnote b of Table 1.

measure of overall error, at least for the present purposes.

In Table 1 the results of the synthetic test are summarized. For each of the two interpolation stations (Tucson, Natural Bridge) and for each of two six-month seasons, a total of seven different series of estimates were made. The first four of each set of seven are single-index-station estimates, the next two are two-index-station estimates, and the last is a four-index-station estimate (that is the summation over k in (1) is taken in this last instance from 1 to 4). The percentage errors, of which 20 were averaged to give each of the entries of Table 1, were obtained by dividing the absolute value of the difference between the individual estimate and the actually reported value by the actually reported value, or in the symbolism of (1), $|P_{ti}) - P_{ij}|$ divided by P_{ij}, where P_{ij} is the true Tucson or Natural Bridge seasonal total and (P_{ij}) the corresponding estimate.

Table 1 reveals nothing about the sense of the departure of estimated value from reported value, since only absolute values enter into that tabulation. Since secular trend effects can be different at two stations for two different periods of time, it has to be admitted that making estimates in an early period such as 1900–1929 but employing means for a recent period such as 1931–1952, introduces possibility of systematic bias in the signs of the errors of estimate. To obtain a rough measure of this type of bias, each of the (fourteen) series of estimates was processed as follows: Using all available estimates for the entire period 1900–1929 for each predictor-season combination, the percentage of positive signs of departure of estimates from reported values were computed separately for each of the fourteen cases. The results are found in Table 2.

Discussion of results—The implications of Tables 1 and 2 may be summarized as follows:

(a) Very generally, all of the error-levels of Table 1 are in the neighborhood of 20–30 pct; that is, it appears that the method of (1) must be expected to yield in the neighborhood of a 25-pct error for estimated seasonal totals in Arizona. Somewhat curiously, this is of the same magnitude as the errors reported by *Paulhus* and *Kohler* [1952] for normal-ratio estimates of storm totals using three index stations. Apparently the smoothing effect of going to longer time periods, as in the present test, is roughly cancelled by lumping together the contribution of many individual storms that give widely variable amounts to the several stations under consideration, a compensation that would have been difficult to anticipate, in the writer's view.

(b) An improvement results, in general, as one increases the number of stations used, that is, as n is increased, but this trend is seen to be a bit erratic, and the gain is not extremely impressive as n increases from one to four.

(c) Distance between index station and interpolation station is not correlated in any very strong way with error of estimation. Thus, for the Tucson winter estimates, Bisbee is the best single-station

estimator, though its distance from Tuscon is twice that for Benson and three times that for Oracle. Similarly Phoenix is the best estimator of Natural Bridge winter data though it is slightly farther from Natural Bridge than either Prescott or Flagstaff. The latter case is additionally surprising inasmuch as Phoenix is well out of the mountainous area within which Natural Bridge, Prescott, and Flagstaff all lie. The correlation coefficient for the relation of Natural Bridge to several other stations was computed for the available periods of record in related study [*McDonald*, 1956] and the results are of some interest here. For winter totals, the correlation with Phoenix was 0.85, which exceeded that for Flagstaff, 0.57, but was slightly smaller than was the value of 0.87 for Prescott. Distance and topographic similarity do not at all emerge as decisive clues to selection of optimal predictors in the present problem.

(d) In general, one sees that estimation is a bit more accurate in winter than in summer in Arizona. Thus, ten of the 14 cases of Table 1 show better estimates in winter than in summer. Again, however, the differences are not uniformly large.

(e) The distribution of algebraic signs of estimation errors, as revealed by Table 2, presents a somewhat confusing picture. No uniform trends appear evident, with the partial exception of the Tucson winter estimates, for which there is a noticeable tendency towards a deficiency of positive errors. It would seem that no very serious bias has been introduced into the present sample of estimates as a consequence of treating the practically important situation wherein one estimates old data using recent means, but beyond that observation, it seems difficult to generalize from Table 2.

Conclusions—On the basis of these results of the empirical test of the estimation scheme of (1), it is concluded that, at least for the Southwest, two index stations should be used as predictors, for the added labor of increasing n beyond two seems scarcely justified. It is further concluded that, if two index stations can be selected from within a radius of 100 miles centered on the station whose missing datum is to be estimated, the relative error of estimate may be expected to be in the neighborhood of 25 pct, on the average.

In most practical applications in studies of precipitation in the Southwest (except for the very earliest periods of record when stations were few and far between), the above requirements can be met. A 25-pct error in a single missing seasonal total, though hardly negligible, is sufficiently small (especially as compared with typical southwestern station coefficients of variation), that definite advantage is, in the writer's opinion, gained by carrying out this type of estimate rather than merely omitting missing periods from analysis.

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On the Damping of Gravity Waves Over a Permeable Sea Bed*

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Abstract—The problem of damping of gravity waves over a permeable sea bed of great depth is re-examined, using a more rigorous approach than that employed by Putnam in 1949. It is found that Putnam's approximate method of analysis is justified in view of the smallness of the permeability factors commonly encountered. However, a misinterpretation error was discovered in Putnam's paper which makes his dissipation function too great by a factor of four.

Introduction—In the classical problem of low-amplitude plane gravity waves in a fluid of finite, uniform depth [see *Lamb*, 1945, pp. 363–370], the bottom is considered impermeable, and the waves are undamped. *Putnam* [1949] found that a significant loss of wave energy, and hence damping, can occur in the presence of a porous sand sea bed owing to the viscous percolation of fluid into the sand, the percolation being activated by the pressure variation along the bottom.

One of the purposes of this paper is to point out an error in Putnam's paper and at the same time to justify his approximate method of analysis of percolation in a porous sea bed. In his analysis, Putnam considered that the percolation in a permeable sea bed caused by gravity waves is governed by Darcy's law for steady flow. In addition he assumed that the pressure variation at the sea-bed interface is the same as that derived from the classical wave theory for undamped waves over an impermeable bottom.

In the following development, the problem of percolation is re-examined from the standpoint of damped waves in a two-layer, coupled system, wherein the pressure and velocity distributions in the upper layer not only govern but are in turn influenced by the percolation in the permeable lower layer. In addition, the acceleration of the flow in the lower layer is considered, although it is found that the effect of such acceleration is negligible for a sea bed of realistic permeability.

List of symbols—The following symbols are used:

A wave amplitude at x
A_0 wave amplitude at $x = 0$
D decay modulus
e 2.71828. . .
g acceleration of gravity
h still-water depth
i $\sqrt{-1}$
K permeability coefficient
k wave number ($2\pi/L$)
L wave length
L_0 deep-water wave length
M see Eq. (14)
m $K\omega/\nu$ (dimensionless)
N $k + iD$
p_0 hydrostatic pressure at $y = 0$, water at rest
p_1 pressure in upper layer
p_2 pressure in permeable medium
p pressure at $y = 0$
R mean rate of dissipation of energy per unit time per unit surface area
r reciprocal of the porosity of the permeable medium (>1)
T wave period
t time
u_1 x-component of velocity in upper layer
u_2 x-component of volume flux in permeable layer
v_1 y-component of velocity in upper layer
v_2 y-component of volume flux in permeable layer
x horizontal coordinate along direction of wave propagation
y elevation above bottom
α constant phase angle (radians), Eq. (26)
β_1 variable phase angle (radians), Eq. (33)
β_2 variable phase angle (radians), Eq. (34)
η anomaly of water level (ft) above still water level
ν kinematic viscosity
π 3.14159. . .
ρ density of the fluid
ϕ velocity potential, upper layer
ψ_1 streamfunction, upper layer
ψ_2 streamfunction, lower layer
ω angular frequency ($2\pi/T$)

Mathematical statement of the problem—Consider a fluid layer of mean depth h overlying a porous medium of uniform permeability and infinite depth (Fig. 1). The x-axis is taken in the plane of the interface, and the y-axis is taken vertically upward. We shall be concerned with low-amplitude, progressive, plane waves advancing in the direction of the x-axis.

If we ignore the influence of viscosity in the upper layer then a velocity potential ϕ exists, the gradient of which equals the velocity of the fluid.

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Under conditions of incompressible flow, the continuity equation takes the form

$$\frac{\partial^2\phi}{\partial x^2} + \frac{\partial^2\phi}{\partial y^2} = 0 \tag{1}$$

and the pressure p_1 in the upper layer is governed by the equation of motion [*Lamb*, 1945, p. 363].

$$\frac{p_1}{\rho} = \frac{\partial\phi}{\partial t} - gh + \text{constant} \tag{2}$$

For the permeable layer we take as the equations of motion

$$r\frac{\partial u_2}{\partial t} = -\frac{\nu}{K}u_2 - \frac{1}{\rho}\frac{\partial p_2}{\partial x} \tag{3a}$$

$$r\frac{\partial v_2}{\partial t} = -\frac{\nu}{K}v_2 - \frac{1}{\rho}\frac{\partial p_2}{\partial y} \tag{3b}$$

It is assumed that the medium is not stratified, so that K and r are constant. Note that for unaccelerated flow, (3ab) reduce to Darcy's law for steady percolation, as utilized by *Putnam* [1949].

Since the flow in the lower layer must also satisfy the continuity equation for incompressible flow, it follows from (3ab) that p_2 is governed by the Laplacian equation

$$\frac{\partial^2 p_2}{\partial x^2} + \frac{\partial^2 p_2}{\partial y^2} = 0 \tag{4}$$

The boundary conditions are taken as follows

$$-\frac{\partial\phi}{\partial y} = \frac{\partial\eta}{\partial t} \quad \left.\right\} \text{at } y = h \text{ (sea surface)} \tag{5}$$

$$\frac{\partial^2\phi}{\partial t^2} + g\frac{\partial\phi}{\partial y} = 0 \quad \left.\right\} \tag{6}$$

$$p_1 = p_2 \quad \left.\right\} \text{at } y = 0 \text{ (interface)} \tag{7}$$

$$-\frac{\partial\phi}{\partial y} = v_2 \quad \left.\right\} \tag{8}$$

$$u_2 = v_2 = 0 \quad \text{at } y = -\infty \tag{9}$$

where $h + \eta$ represents the elevation of the free surface above bottom at position x and time t, η being considered small relative to h. Condition (6) follows from the assumption of constant surface pressure and (2) and (5) [*Lamb*, 1945, p. 364].

Solution for simple harmonic, exponentially damped waves—We will consider a surface disturbance of the form

$$\eta = A_0 e^{i(Nx-\omega t)} \tag{10}$$

where it is understood that only the real part on the right is taken. Thus if A_0 and ω are real and

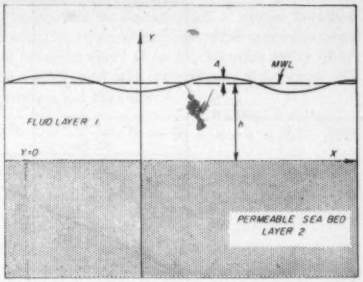

FIG. 1 – Schematic of two-layer system indicating coordinates

N is a complex wave number given by

$$N = k + iD \tag{11}$$

then the real part of (10) can be written

$$\eta = A_0 e^{-Dz}\cos(kx - \omega t) \tag{12}$$

which is clearly a progressive wave of period $2\pi/\omega$, phase velocity ω/k, and amplitude $A_0 e^{-Dz}$.

Since the problem is linear, all of the variables are periodic with frequency ω and hence we can write (3ab) in the form

$$u_2 = -\frac{M}{\rho\omega}\frac{\partial p_2}{\partial x} \tag{13a}$$

$$v_2 = -\frac{M}{\rho\omega}\frac{\partial p_2}{\partial y} \tag{13b}$$

where

$$M = \frac{m}{1 - imr} = \frac{m + irm^2}{1 + (mr)^2} \tag{14}$$

and

$$m = \frac{K}{\nu}\omega \tag{15}$$

the latter quantity being the fundamental dimensionless permeability modulus of the problem.

By making use of (10) and (13ab) it can be verified that the solutions for ϕ and p_2 which exactly satisfy the Laplacian equations and all but one of the boundary conditions are given by the real parts of

$$\phi = \frac{igA_0}{\omega}\frac{\cosh Ny - iM\sinh Ny}{\cosh Nh - iM\sinh Nh}e^{i(Nx-\omega t)} \tag{16}$$

$$p_2 = p_0 + \rho g A_0 \frac{e^{Ny+i(Nx-\omega t)}}{\cosh Nh - iM\sinh Nh} \tag{17}$$

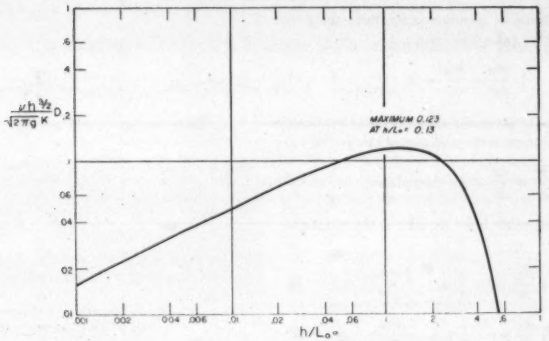

FIG. 2 – Graph of the dimensionless decay parameter $(\nu h^{3/2}/K\sqrt{2\pi g})D$ versus the relative depth parameter h/L_0 as deduced from (15), (20), and (21); D is the decay modulus in the expression e^{-Dx} (see list of symbols for other parameters)

These relations will satisfy all of the boundary conditions provided that N satisfies the relation

$$\frac{\omega^2}{g} = N\frac{\sinh Nh - iM\cosh Nh}{\cosh Nh - iM\sinh Nh} \tag{18}$$

This equation represents the basic Hamiltonian relation of the problem, from which it is possible to determine both k and D in terms of ω, h, and K/ν.

Wave length and decay modulus for small values of m—The permeability K for ordinary sand is of the order of magnitude of 10^{-9} ft^2 (which is about 100 darcys). Furthermore the value of ν for water is approximately 10^{-5} ft^2/sec, and hence m is of the order of $10^{-4}\omega$. Thus even for a wave having a period as low as 0.5 sec ($\omega = 4\pi$ rad/sec) the dimensionless parameter m will be only of the order of 10^{-3}. If we consider that rm is also small (of the order of 10^{-2} or less) and neglect all terms of the order rm^2 or smaller, then M reduces to m by (14). We would get the same result if we had neglected the acceleration in the permeable layer originally.

Eq. (18) must be satisfied identically, and consequently the imaginary part of the expression on the right must vanish. We can, without too much difficulty, separate the right-hand side into real and imaginary parts, and if we neglect terms of the order of m^2 or smaller we find from the imaginary part of (18)

$$\frac{\sin 2(m - Dh)}{2Dh} = \frac{\sinh 2kh}{2kh} \tag{19}$$

The quantity on the right is a function of kh only and is always greater than or equal to unity, and since m is considered to be of the order of 10^{-2} or less, it follows that there is only one solution for Dh and this must be less than m. Consequently $\sin 2(m - Dh)$ can be replaced by $2(m - Dh)$ and we find

$$Dh = m\left(\frac{2kh}{2kh + \sinh 2kh}\right) \tag{20}$$

From (20) we see that Dh is less than or at most equal to $m/2$ under the conditions of small m. Consequently we can neglect terms of the order $(Dh)^2$ or smaller as well as m^2 in the real part of (18) and we find that kh must satisfy the relation

$$kh\tanh kh = \omega^2 h/g \tag{21}$$

which is identical to the classical relation for an impermeble bottom. Thus the percolation has negligible effect on the wave length, phase velocity, and group velocity of the surface disturbance, as anticipated tacitly by *Putnam* [1949].

From (20) and (21) we see that Dh/m is a function of the dimensionless parameter $\omega^2 h/g$ and consequently is a function of h/L_0 where L_0 is the deep-water wave length defined by $2\pi g/\omega^2$. Furthermore in view of (15) it follows that the dimensionless quantity $(\nu h^{\frac{1}{2}}/K\sqrt{2\pi g})D$ is a function of h/L_0 only. A plot of this function is given in Figure 2. Note that the maximum decay rate, for a given depth and given permeability, occurs for the relative depth $h/L_0 = 0.13$, which implies that for a given depth there is a particular period

for which the waves have the greatest attenuation due to percolation.

As a specific example, consider water of ten-foot depth with a sand bottom for which $K/\nu = 10^{-4}$ sec. The period corresponding to maximum attenuation is $\sqrt{2\pi h/0.13g}$ or about 3.9 sec. The decay modulus D for this condition, by Figure 2, is $0.123\sqrt{2\pi gK/\nu h}$ or about 0.55×10^{-5} ft^{-1}. Thus in a distance of 10,000 ft the wave amplitude decays from A_0 to $0.947A_0$, and for twice the above distance, the amplitude will be reduced to $0.898A_0$, assuming the depth remains constant over this distance. If the depth were five feet the maximum decay modulus would be 2.83 times as great, and this would occur for waves of 2.74-sec period.

The reason for the maximum decay for intermediate relative depth lies in the fact that the pressure gradient which motivates the percolation has its maximum value (for a given wave amplitude and depth) at intermediate periods. The maximum range of pressure variation at the bottom for given amplitude and depth occurs for the longest-period waves, and virtually no pressure variation occurs for very short waves. However the magnitude of the pressure gradient depends upon the ratio of the pressure range and the wave length and hence this gradient is accordingly small for both large and small waves and must have a maximum value for waves of intermediate length or period.

In view of the above discussion, it is apparent that a wave group which contains many different frequencies will suffer a peculiar type of selective attenuation wherein the energy spectrum is altered (diminished) for a certain intermediate range of frequencies and remains essentially unchanged in the region of high and low frequencies.

Energy dissipation—The mean rate of energy dissipation R for a vertical column of unit surface area and infinite depth can be computed in several different ways. One method is to evaluate the mean work done by the upper fluid on the fluid within the permeable layer per unit area of the interface as follows

$$R = -(1/T)\int_0^T pv\,dt \qquad \text{at } y = 0 \quad (22)$$

where T is the wave period $2\pi/\omega$. The value of v at $y = 0$ can be evaluated from either ϕ or p_2 as follows

$$v = -\left(\frac{\partial\phi}{\partial y}\right)_{y=0} = -\frac{M}{\rho\omega}\left(\frac{\partial p_2}{\partial y}\right)_{y=0}$$

$$= \frac{igA_0NMe^{i(Nz-\omega t)}}{\omega(\cosh Nh - iM\sinh Nh)} \quad (23)$$

The pressure at the interface is readily obtained from (17). If we employ the same approximations as before (neglect terms of the order m^2 or $(Dh)^2$ or smaller) and take the real part of (23) and (17) then we find that at $y = 0$

$$v = -\frac{gA_0km}{\omega\cosh kh}e^{-Dx}\cos(kx - \omega t + \alpha + D/k) \quad (24)$$

and

$$p = p_0 + \frac{\rho gA_0e^{-Dx}}{\cosh kh}\cos(kx - \omega t + \alpha) \quad (25)$$

where

$$\alpha = (m - Dh)\tanh kh \quad (26)$$

Both D/k and α are much less than unity, so that v and p are only slightly out of phase with each other and with the surface disturbance.

Using (24) and (25) in (22) gives

$$R = \frac{\rho g^2km\,A^2}{2\omega\cosh^2 kh}\cos(D/k) \quad (27)$$

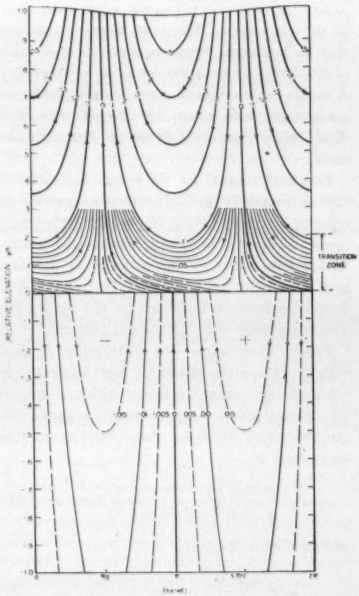

FIG. 3 – Isolines of relative streamfunction ψ/ψ_0 for both layers versus relative elevation and phase position; $\psi_0 = gA_0/\omega\cosh kh$, as deduced from (31) and (32); this plot is for the case of m= 0.02 and h/L$_0$ = 0.05, the vertical scale being exaggerated to emphasize the transitional region near the interface

where $A = A_0 e^{-Dz}$ is the amplitude at any position x. The term $\cos(D/k)$ can be taken as unity to the same degree of approximation as that utilized in deriving (24) and (25). Substituting for m and $k = 2\pi/L$, and making the above approximation gives finally

$$R = \frac{\pi \rho g^2 K A^2}{L\omega \cosh^2 kh} \tag{28}$$

The formula for dissipation found by *Putnam* [1949] is the same except that he has wave height H in place of the amplitude A. The authors are convinced that Putnam's formula is erroneous and stems from an earlier misinterpretation error in his Eq. (6) where he gives in effect the amplitude of the variation of p/ρ at $y = 0$. In that equation he has H instead of $H/2$ as given by the classical wave theory. Unfortunately the formula for wave power employed by Putnam contains H correctly so that the error does not cancel out in his analysis of the wave decay. We must therefore conclude that his numerical examples apply for a K value of 400 darcys and not 100 darcys as he stipulates. A similar error occurs in regard to the graphs for percolation loss given by *Bretschneider* and *Reid* [1954] which were based on Putnam's formula.

Empirical support for the energy loss function (28) is found in the laboratory measurements reported by *Savage* [1953]. In comparing the measurements of energy loss by percolation with theory, Savage found that for the majority of the data good agreement was obtained if Putnam's energy dissipation function is divided by the factor four. This is precisely what (28) would indicate.

Velocity distribution—The distribution of fluid velocity at a given instant is best illustrated in terms of the stream-function ψ which is defined by the relations $u = -\partial\psi/\partial y$ and $v = \partial\psi/\partial x$. The streamfunction satisfying these relations for the upper layer is

$$\psi_1 = -\frac{gA_0}{\omega}\frac{\sinh Ny - iM\cosh Ny}{\cosh Nh - iM\sinh Nh} e^{i(Nx-\omega t)} \tag{29}$$

and for the lower layer

$$\psi_2 = \frac{igA_0 M}{\omega}\frac{e^{Ny+i(Nx-\omega t)}}{\cosh Nh - iM\sinh Nh} \tag{30}$$

If we ignore terms of the order m^2 or smaller as before and take the real parts we find

$$\psi_1 = -\frac{gA_0}{\omega}\frac{\sinh ky}{\cosh kh} e^{-Dz}\cos[kx - \omega t + \beta_1(y)] \tag{31}$$

and

$$\psi_2 = -\frac{gA_0 m}{\omega}\frac{e^{ky}}{\cosh kh} e^{-Dz}\sin[kx - \omega t + \beta_2(y)] \tag{32}$$

where

$$\tan\beta_1(y) = \alpha - (m - Dy)\coth ky \tag{33}$$

$$\tan\beta_2(y) = \alpha + Dy \tag{34}$$

and α is given by (26). The phase angle β_1 varies rapidly from about $-\pi/2$ radians to nearly zero in a short distance above the interface. A plot of the streamfunction isolines (or streamlines) for the case of $m = 0.02$ and $h/L_0 = 0.05$ is shown in Figure 3. The value of m was purposely taken large in order to exaggerate the thickness of the transitional region near the interface. It will be noted that the horizontal velocity at the bottom is nearly $\pi/2$ radians out of phase with the surface disturbance and that a discontinuity in the magnitude of the horizontal velocity occurs across the interface as reflected in the abrupt change in slope of the streamlines. The streamline picture agrees with that of *Putnam* [1949] if the transitional layer thickness is visualized as extremely small ($m \to 0$), such that a discontinuity in phase angle occurs at the interface.

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Wave Measurements along the California Coast

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Abstract—The heights and periods of waves were measured at Davenport, California, between July 1953 and November 1954, mostly by means of a surface-type wave gage. Certain results, expressed in terms of the ratios of maximum, average of the highest one-tenth, and mean wave heights to the average of the highest one-third of the waves for specified time intervals, are compared with similar published data obtained by bottom pressure recorders; these ratios were found to be lower than the ratios from the bottom pressure recorder records. In addition, a few months' wave records are presented for Pt. Arguello, Pt. Sur, and Pt. Pinos, California.

Introduction—As in all phases of oceanography, there is a lack of detailed measurements of waves. These measurements are necessary to determine the 'wave climate' of a region. During the course of a study of wave transformation in shoaling water performed by the University of California for the Office of Naval Research [*Wiegel* and *Fuchs*, 1955] it was possible to make nearly continuous measurements of waves from July 1953 to the middle of November 1954 at Davenport, California. Some hitherto unpublished records obtained as a part of another study at Pt. Arguello, Pt. Sur, and Pt. Pinos, California [*Wiegel*, 1949] have been included.

Wave records—Some of the Davenport data were obtained by ocean-bottom pressure-type recorders [*Snodgrass*, 1956], but most of the data were obtained by means of a recorder which measured directly the surface time history [*Caldwell*, 1956]. The surface-type wave recorders which were used were calibrated at about two- to four-week intervals. The instruments were installed in water 46 ft deep (below MLLW) off the end of a 2200-ft pier in a region exposed to the large waves from the North Pacific area (Fig. 1). The wave records were analyzed for approximately a 15- to 20-min interval, usually every 12 hr. The results are given in Figure 2. The data are presented in terms of significant wave height and period [*Wiegel*, 1953]. They have not been adjusted to deep-water conditions.

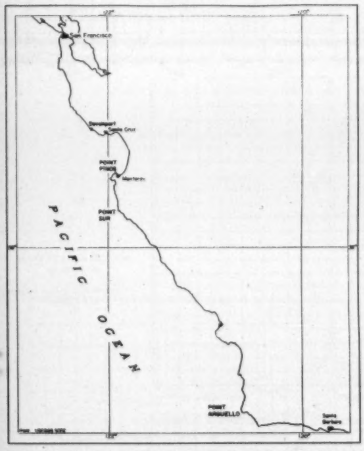

FIG. 1 — Locations of wave recorders along California Coast

The wave recorder at Pt. Arguello was located at the bottom 80 ft below MLLW. This was five feet deeper than the original wave recorder at Pt. Arguello. The wave recorder at Pt. Sur was located at the bottom 62 ft below MLLW. The wave recorder at Pt. Pinos was located at the bottom 35 ft below MLLW. University of California Mark III bottom pressure-type wave recorders were used [*Folsom*, 1949; *Snodgrass*, 1951]. In Figure 3 are presented the wave data for these three locations. The Pt. Sur and Pt. Pinos records were analyzed for approximately a 20-min interval once a day, and the Pt. Arguello records were analyzed twice a day. The significant wave height is plotted for Pt. Arguello and Pt. Pinos, while the average of the highest ten per cent is plotted for Pt. Sur.

Statistical relationships—In recent years several papers have been published which show the relationships among maximum wave height, significant wave height, mean wave height, etc., obtained from wave measurements [*Ehring*, 1940; *Wiegel*, 1949; *Rudnick*, 1951; *Munk* and *Arthur*, 1951; *Darbyshire*, 1952; *Putz*, 1952; *Pierson* and *Marks*, 1952; *Watters*, 1953; *Yoshida*, *Kajiura*, and

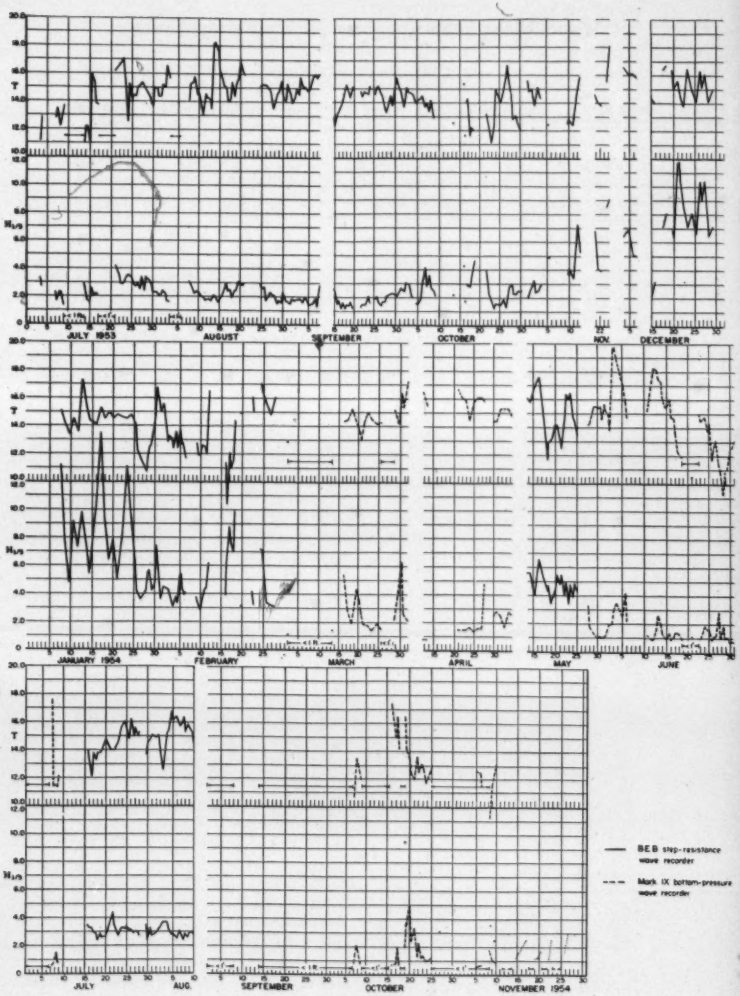

FIG. 2—Height and period of waves measured at Davenport, California

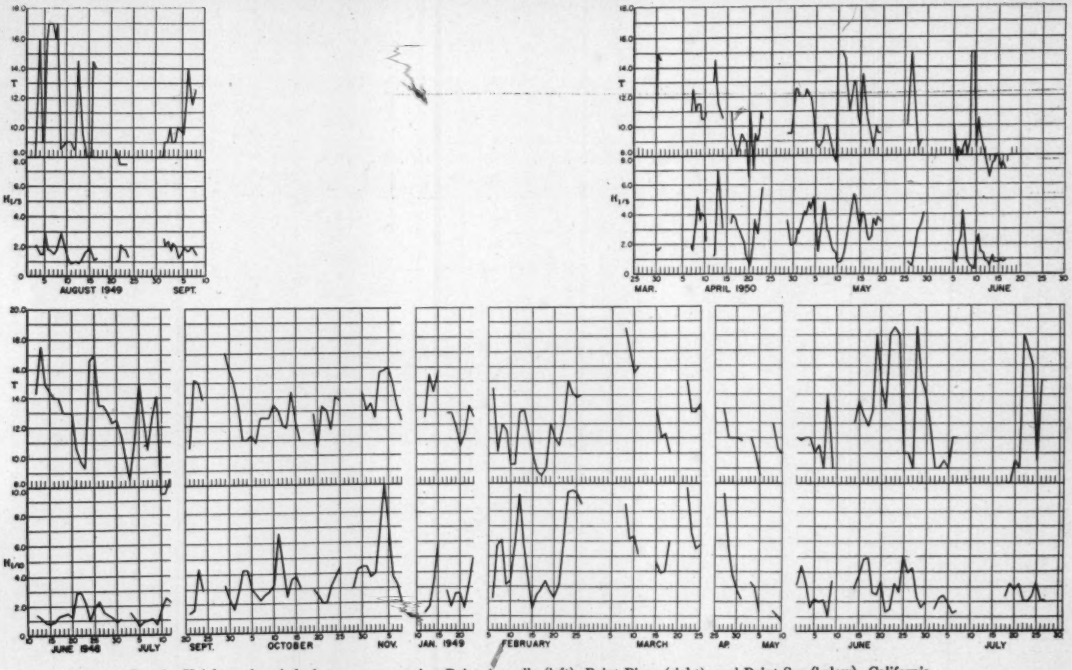

FIG. 3—Height and period of waves measured at Point Arguello (left), Point Pinos (right), and Point Sur (below), California

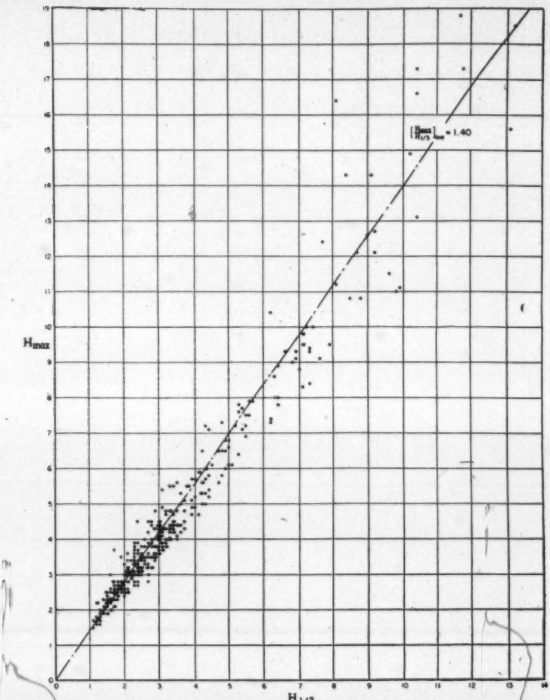

FIG. 4 — Relationship between maximum wave and significant wave heights, BEB step-resistance wave recorder (surface), Davenport, California

Hidaka, 1953; and *Darlington*, 1954]. These papers advanced the concept of the 'statistical nature' of ocean waves. Many of the data were summarized by *Longuet-Higgins* [1952] in his theoretical paper on the statistical distribution of the heights of ocean waves. Almost all of the data were obtained from bottom pressure-type recorders, however, with their inherent practical and theoretical difficulties [*Folsom*, 1949; *Pierson* and *Marks*, 1952; and *Gerhardt*, *Jehn* and *Katz*, 1955].

Most of the Davenport data were obtained from a surface time history type of recorder. These data were used to construct Figures 4, 5, and 6, which show the relationships between the significant wave height and maximum wave height measured during the recording interval, the significant wave height $H_{1/3}$ and the average of the highest ten per cent of the waves $H_{1/10}$ measured during the recording interval, and the significant wave height and the mean height of waves H_{mean} measured during the recording interval. The ratios were found to be: $H_{max}/H_{1/3} = 1.40$, $H_{max}/H_{mean} = 1.90$, $H_{1/10}/H_{1/3} = 1.19$ and $H_{1/3}/H_{mean} = 1.37$.

These data have been compared in Table 1 with data obtained by investigators for other locations. It can be seen that the ratios obtained by the surface recorder are lower than those obtained by the bottom pressure recorders or the ship-borne recorder.

For a portion of the time none of the surface wave recorders was in operation. A University of California Mark IX bottom-pressure recorder was

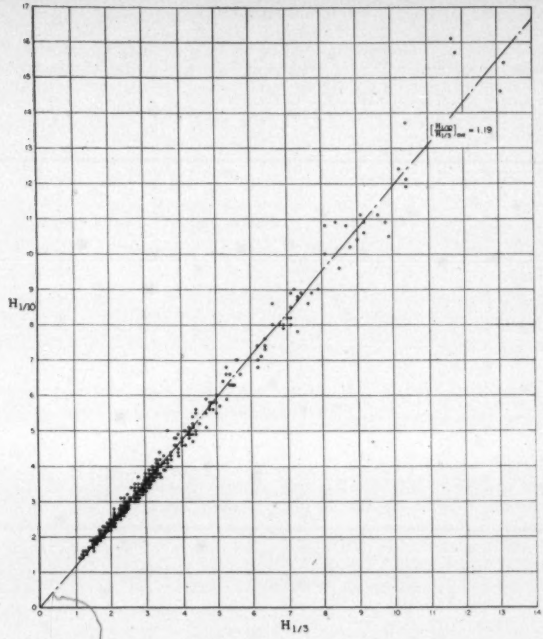

FIG. 5 — Relationship between average of highest ten per cent and significant wave heights, BEB step-resistance wave recorder (surface), Davenport, California.

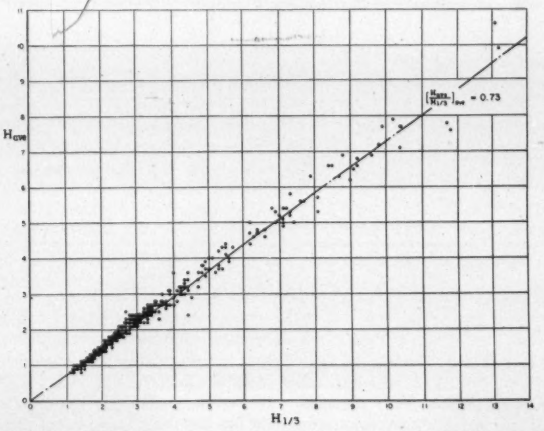

FIG. 6 — Relationship between average wave and significant wave heights, BEB step-resistance wave recorder (surface), Davenport, California

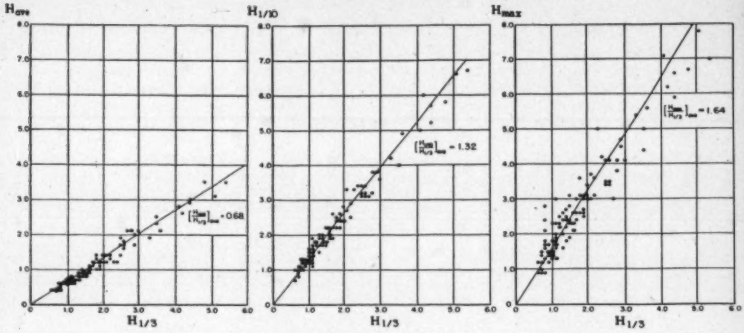

FIG. 7—Relationships among H_{max}, $H_{1/10}$, $H_{1/3}$, and H_{ave} for Mark IX bottom pressure recorder, Davenport, California

installed in the same location. The data have been presented in line 1b of Table 1. It can be seen that these ratios are similar to the ratios obtained from the other wave recorders, but not by the surface wave recorder at Davenport.

A graphical representation of the various height parameters obtained from the bottom pressure recorder is shown in Figure 7 which presents plots similar to Figures 4–6 for the surface recorder.

Three different BEB surface wave recorders were used to obtain the data presented herein, and a study of the wave-height ratios showed no variation with the particular wave recorder used. The BEB surface wave recorders were only 20 ft long; this limit, together with the tide variation, limited the maximum wave height that could be recorded to between 14 and 20 ft, depending upon the tide stage. The data on the few occasions for which the maximum wave height could not be obtained for this reason were not used to determine the wave height ratios. The outputs of the BEB surface wave recorders are not exactly linearly related to the change in water-surface elevation; however, the records were analyzed by means of a transparent overlay which rectified the non-linearity so the wave height ratios do not reflect the non-linearity.

It is believed that the difference in wave-height ratios is because the dynamic pressure at the bottom due to the waves is less for the shorter-period than for the longer-period waves for a given wave height [*Folsom*, 1949]. An 'average' wave period of some type is used to derive the multiplication factor by which the bottom pressures are transformed into surface wave heights. The significant period is longer than the mean period (the significant period being associated with the groups of large waves in the record [*Darlington*, 1954]). Thus the lower multiplication factor associated with the longer, higher waves is used to transform the pressure records of the more numerous lower (and on the average, shorter) waves to their surface representation. This would result in a greater number of waves listed as lower in height than would be the actual case, while there would be a lesser number of waves listed as higher in height than would be the actual case. This, in turn, would result in H_{max}/H_{mean}, $H_{1/3}/H_{mean}$, etc., being greater for a subsurface recorder than for a surface recorder.

Similar reasoning can be applied to the ship-borne wave recorder as one component of the recorder consists of a pressure tap ten feet or so below the water surface; this tends to record a lower height of low-period waves than the actual wave height [*Tucker*, 1956].

Conclusions—The ratios of maximum wave height to mean wave height, average height of the highest one-third of the waves to the mean wave height, etc., as obtained from a surface wave recorder were lower than the same ratios obtained by bottom-pressure type recorders and a ship-borne wave recorder. It is believed that the difference, and the sign of the difference, can be explained by the method of analyzing the records of the bottom pressure wave recorders combined with the fact that the subsurface dynamic pressures de-

TABLE 1 — *Measured statistical ratios for ocean waves*

Location and type wave recorder	Statistical ratios							Remarks
	$\frac{H_{max}}{H_{1/10}}$	$\frac{H_{max}}{H_{1/3}}$	$\frac{H_{max}}{H_{mean}}$	$\frac{H_{1/10}}{H_{1/3}}$	$\frac{H_{1/10}}{H_{mean}}$	$\frac{H_{1/3}}{H_{mean}}$	$\frac{H_{9/10}}{H_{mean}}$	
1a. Davenport, Cal.; surface		1.40	1.90	1.19	1.61	1.37		11 mo, 12–20 min interval every 12 hr, water depth 46 ft MLLW
1b. Davenport, Cal.; bottom-pressure		1.64	2.64	1.32	2.09	1.48		5 mo., 12–20 min interval every 12 hr., recorder in 46 ft water MLLW
2. N. Atlantic Oc.; NIO ship-borne			2.40			1.60		138 records, 26–124 waves/record (mean of 69 waves) every 3 hr [*Darlington*, 1954]
3. Pt. Arguello, Cal.; bottom-pressure	1.42	1.85		1.30				3 mo, 20 min. every 8 hr, figures refer to daily ave. and max., wave rec'dr in 75 ft of water MLLW [*Wiegel*, 1949]
4. Pt. Sur, Cal.; bottom-pressure	1.46	1.85		1.27				14 mo, 20 min. interval every 8 hr, figures refer to daily ave. and max., recorder in 68 ft of water MLLW [*Wiegel*, 1949]
5. Heceta Head, Ore.; bottom-pressure	1.47	1.91		1.30				14 mo, 20 min. interval every 8 hr, figures refer to daily ave. and max. wave rec'dr in 50 ft of water MLLW [*Wiegel*, 1949]
6. Cuttyhunk, Mass.; bottom-pressure						1.57		10 mo, 20 min. interval every 6 hr, wave rec'dr in 75 ft of water [*Seiwell*, 1948]
7. Bermuda; bottom-pressure						1.57		4 mo, 20 min. interval every 2 hr, wave rec'dr in 120 ft of water [*Seiwell*, 1948]
8. Cape Cod, Mass.							1.56	1 record, 14 waves; 1 record, 28 waves; waves only 2–3 sec period [*Gibson*, 1944]
9. LaJolla, Cal.; bottom-pressure		1.63				1.49		46 waves [*Munk* and *Arthur*, 1951]
10. North Sea; pressure hanging on cable below float						1.85		688 waves (every bump counted as a wave); wind waves [*Ehring*, 1940]
		1.5				(1.58)		517 waves (neglecting all waves less than 14.8 cm. high in above sample [*Harney*, *Saur*, and *Robinson*, 1949]
11. Pacific Coast, US, and Guam; MI bottom pressure						1.63		25 records, 20-min interval [*Putz*, 1952]
12. Greymouth, N. Z.; bottom-pressure				1.24	1.94	1.58		109 records, each of 17-min. interval, every 2 hr [*Walters*, 1953]
13. Hachijo I., Japan; (surface?)			2.0			1.5		11 records, each of 10-min. interval various locations [*Yoshida*, *Kajiura*, and *Hidaka*, 1953]
14. Long Branch, N. J.; BEB surface		1.29	1.93			1.50		1 record of 102 waves [*Pierson*, *Neumann*, and *James*, 1955]
15. Bermuda; NIO ship-borne				1.24		1.61		6 records, 12–18 min interval [*Farmer*, 1956]
16. Oceanside, Cal.; bottom-pressure				1.25				1 mo, 20-min interval every 8 hr (unpublished data).

crease more rapidly with depth for the lower-period waves than for the longer-period waves.

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On the Offshore Distribution of Tide and Tidal Current*

MAURICE RATTRAY, JR.

Abstract—The tides and tidal currents in offshore regions where the frictional effect is negligible are obtained from the tides at the adjacent shore stations by an approximate solution of the tidal equations. Application of the method to two known conditions gives good results where friction is negligible, but rather poor results for the longshore current where friction cannot properly be neglected.

Introduction—Our present fragmentary knowledge of the distribution of tide and tidal current in offshore regions is based mainly on relatively few series of measurements made at lightship stations. The predominantly rotary nature of these currents indicates the importance of the Earth's rotation and shows that studies, such as *Fleming's* [1938] on the tide in the Gulf of Panama where this factor is unimportant, are not generally applicable for use along more open coasts in the higher latitudes. Other theories which consider the effect of the Earth's rotation are unable to satisfy the boundary conditions imposed by the coast.

The purpose of this paper is to develop methods, when the effect of friction is negligible, whereby the offshore distribution of tide and tidal current can be determined from a knowledge of the tide and normal component of the tidal current along the adjacent shoreline. An example is given to demonstrate the application of the methods to a known case.

Formulation of the problem—Over a sufficiently small region, where the direct tide-generating forces and friction can be neglected, the differential equations describing a simple harmonic tide are [*Lamb*, 1932; pp. 318–319]:

$$h\left(\frac{\partial^2\zeta}{\partial x^2}+\frac{\partial^2\zeta}{\partial y^2}\right)+\left(\frac{\partial h}{\partial x}+i\frac{2\omega}{\sigma}\frac{\partial h}{\partial y}\right)\frac{\partial\zeta}{\partial x}+\left(\frac{\partial h}{\partial y}-i\frac{2\omega}{\sigma}\frac{\partial h}{\partial x}\right)\frac{\partial\zeta}{\partial y}+\frac{(\sigma^2-4\omega^2)}{g}\zeta=0 \quad (1)$$

$$S=gh\left(i\sigma\frac{\partial\zeta}{\partial x}+2\omega\frac{\partial\zeta}{\partial y}\right)(\sigma^2-4\omega^2)^{-1} \quad (2)$$

$$T=gh\left(i\sigma\frac{\partial\zeta}{\partial y}-2\omega\frac{\partial\zeta}{\partial x}\right)(\sigma^2-4\omega^2)^{-1} \quad (3)$$

where

$e^{i\sigma t}$ time factor

x, y cartesian coordinates of position

S, T x and y components of horizontal transport of the water column per unit width

t time

ζ elevation of the free surface

σ 2π/period

ω local vertical component of the earth's angular velocity of rotation

g acceleration due to gravity

h mean local depth of water

For simplicity, the adjacent shoreline is taken to be straight and to lie on the y-axis. Then the boundary conditions to be satisfied at $x = 0$ become

$$S = 0 \quad (4)$$

$$\zeta = Z(y) \quad (5)$$

where $Z(y)$ is known.

Solution—The depth $h(x)$, the tidal elevation $\zeta(x, y)$, and the transport components $S(x, y)$, are taken to be functions of position such that they can be expanded into Maclaurin's series in two variables. Then, over the area under consideration, the first few terms of the series are used as an approximation as follows

$$\zeta(x,y)=\zeta_{00}+\zeta_{10}x+\zeta_{01}y+\tfrac{1}{2}(\zeta_{20}x^2+2\zeta_{11}xy+\zeta_{02}y^2)+\tfrac{1}{6}(\zeta_{30}x^3+3\zeta_{21}x^2y+3\zeta_{12}xy^2+\zeta_{03}y^3) \quad (6)$$

$$S(x,y)=S_{00}+S_{10}x+S_{01}y+\tfrac{1}{2}(S_{20}x^2+2S_{11}xy+S_{02}y^2) \quad (7)$$

$$T(x,y)=T_{00}+T_{10}x+T_{01}y+\tfrac{1}{2}(T_{20}x^2+2T_{11}xy+T_{02}y^2) \quad (8)$$

$$h(x)=h_0+h_1x+\frac{h_2}{2}x^2 \quad (9)$$

The problem is now solved by equating coefficients of equal powers of x and y when (6), (7), (8), and (9) are substituted into (1), (2), (3), (4), and (5). Use of (5) yields immediately

$$\zeta_{00}=Z(0) \quad (10)$$

* Contribution No. 209 from the Department of Oceanography of the University of Washington.

$$\zeta_{01} = dZ(0)/dy \tag{11}$$

$$\zeta_{02} = d^2Z(0)/dy^2 \tag{12}$$

$$\zeta_{03} = d^3Z(0)/dy^3 \tag{13}$$

Under conditions where the depth distribution requires a finite value for h_0, the following relations are obtained from (2) and (4)

$$\zeta_{10} = i(2\omega/\sigma)\zeta_{01} \tag{14}$$

$$\zeta_{11} = i(2\omega/\sigma)\zeta_{02} \tag{15}$$

$$\zeta_{12} = i(2\omega/\sigma)\zeta_{03} \tag{16}$$

Where $h_0 = 0$, the values for these coefficients are obtained from (1). In both cases (1) is used to give

$$h_0(\zeta_{20} + \zeta_{02}) + h_1\left(\zeta_{10} - i\frac{2\omega}{\sigma}\zeta_{01}\right) + \frac{\sigma^2 - 4\omega^2}{g}\zeta_{00} = 0 \tag{17}$$

$$h_0(\zeta_{21} + \zeta_{03}) + h_1\left(\zeta_{11} - i\frac{2\omega}{\sigma}\zeta_{02}\right) + \frac{\sigma^2 - 4\omega^2}{g}\zeta_{01} = 0 \tag{18}$$

$$h_0(\zeta_{30} + \zeta_{12}) + h_1(\zeta_{20} + \zeta_{02}) + h_2\left(\zeta_{10} - i\frac{2\omega}{\sigma}\zeta_{01}\right) + h_1\left(\zeta_{20} - i\frac{2\omega}{\sigma}\zeta_{11}\right) + \frac{\sigma^2 - 4\omega^2}{g}\zeta_{10} = 0 \tag{19}$$

When $h_0 = 0$, the coefficients of the cubic terms in the expansion for ζ are found from the following relations from (1):

$$h_1\left(\zeta_{12} - i\frac{2\omega}{\sigma}\zeta_{03}\right) + \frac{\sigma^2 - 4\omega^2}{g}\zeta_{02} = 0 \tag{20}$$

$$h_1(\zeta_{21} + \zeta_{03}) + h_1\left(\zeta_{21} - i\frac{2\omega}{\sigma}\zeta_{12}\right) + h_2\left(\zeta_{11} - i\frac{2\omega}{\sigma}\zeta_{02}\right) + \frac{\sigma^2 - 4\omega^2}{g}\zeta_{11} = 0 \tag{21}$$

$$2h_1(\zeta_{30} + \zeta_{12}) + h_2(\zeta_{20} + \zeta_{02}) + h_1\left(\zeta_{30} - i\frac{2\omega}{\sigma}\zeta_{21}\right) + 2h_2\left(\zeta_{20} - i\frac{2\omega}{\sigma}\zeta_{11}\right) + h_3\left(\zeta_{10} - i\frac{2\omega}{\sigma}\zeta_{01}\right) + \frac{\sigma^2 - 4\omega^2}{g}\zeta_{20} = 0 \tag{22}$$

The tidal elevation over the selected region is given by substituting directly into (6) the coefficients obtained above. The transport components are evaluated from (6), (7), and (8) by means of (2) and (3). The current velocities are obtained by dividing the transports by the depth at the particular location.

Example—Consider the determination of the mean semidiurnal tidal current at Umatilla Reef Light Vessel (48°10′ N, 124°50′ W) off the Washington coast. Figure 1 shows its location and the coordinate axes used in this example. Figure 2 gives the mean range and time of tide at adjacent tide stations as obtained from *U. S. Coast & Geodetic Survey* [1956a]. The solid lines indicate the coastal values which are used in the present computations. With 48°10′ N taken as the origin of the coordinate system, and time measured from its time of *HW*, the expressions describing these tides are

$$Z(0) = 3.0 \text{ ft} \tag{23}$$

$$dZ(0)/dy = (9.4 + i7.5) \times 10^{-3} \text{ ft/mi} \tag{24}$$

$$d^2Z(0)/dy^2 = (-1.9 + i4.7) \times 10^{-5} \text{ ft/mi}^2 \tag{25}$$

$$d^3Z(0)/dy^3 = (-17.7 - i4.8) \times 10^{-8} \text{ ft/mi}^3 \tag{26}$$

An average bottom profile for this area is shown in Figure 3. An anomaly occurs at Cape Alava, but this can be expected to have only a minor local effect which is neglected here. The bottom profile is approximated by one of constant slope in the x-direction only, as indicated by the dashed line. It is evident that the approximation to be used for greater distances from the coast could be improved by adding more terms in the expansion for the depth. The equation for the depth profile used here is given by

$$h(x) = h_1 x \tag{27}$$

where $h_1 = 34$ ft/mi.

The tidal elevation in feet and the transports in knot feet for the semidiurnal tide are then

$$\zeta = 3.0 + (-6.5 + i7.0) \times 10^{-3}x + (9.4 + i7.5) \times 10^{-3}y + (0.8 - i1.9) \times 10^{-5}x^2 + (-3.8 - i1.6) \times 10^{-5}xy + (-0.9 + i2.4) \times 10^{-5}y^2 \tag{28}$$

$$S = -i1.5x + (1.7 + i0.3) \times 10^{-2}x^2 + (0.3 - i0.5) \times 10^{-2}xy \tag{29}$$

$$T = (-4.4 + i7.1)x + (0.7 - i1.5) \times 10^{-2}x^2 + (-3.1 - i1.2) \times 10^{-2}xy \tag{30}$$

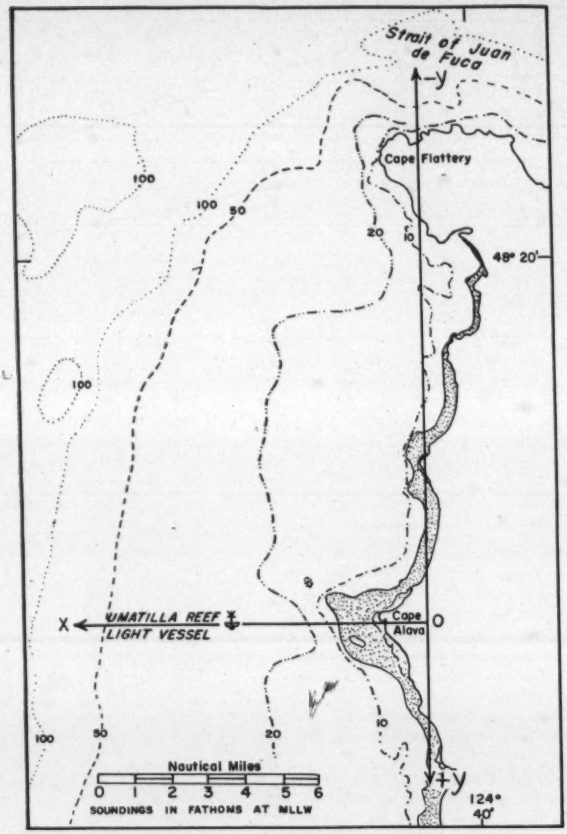

FIG. 1 — Location of the Umatilla Reef Light Vessel

With inclusion of the time factor, the actual amplitude and transports become

$$\zeta = (3.0 - 6.5 \times 10^{-3}x + 9.4 \times 10^{-3}y + 0.8 \times 10^{-5}x^2 - 3.8 \times 10^{-5}xy - 0.9 \times 10^{-5}y^2) \cos \sigma t + (-7.0 \times 10^{-3}x - 7.5 \times 10^{-3}y + 1.9 \times 10^{-5}x^2 + 1.6 \times 10^{-5}xy - 2.4 \times 10^{-5}y^2) \sin \sigma t \quad (31)$$

$$S = (1.7 \times 10^{-3}x^2 + 0.3 \times 10^{-3}xy) \cos \sigma t + (1.5x - 0.3 \times 10^{-3}x^2 + 0.5 \times 10^{-3}xy) \sin \sigma t \quad (32)$$

$$T = (-4.4x + 0.7 \times 10^{-3}x^2 - 3.1 \times 10^{-3}xy) \cos \sigma t + (-7.1x + 1.5 \times 10^{-3}x^2 + 1.2 \times 10^{-3}xy) \sin \sigma t \quad (33)$$

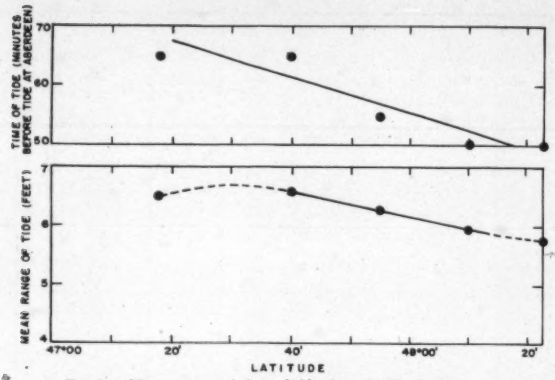

FIG. 2. — Mean range and time of tide along the Washington coast

The currents in knots at Umatilla Reef Light Vessel, calculated by setting $x = 5$ mi and $h = 155$ ft, are

$$u = 0.003 \cos \sigma t + 0.048 \sin \sigma t \qquad (34)$$

$$v = -0.14 \cos \sigma t - 0.23 \sin \sigma t \qquad (35)$$

These currents are plotted as an ellipse in Figure 4. For comparison, the current ellipse obtained by direct measurement [*Marmer*, 1926] is also included. The agreement can be considered excellent. The differences are explainable, at least qualitatively, by the effect of the diurnal tide. Unfortunately, information available to the writer concerning the times of the diurnal tide is insufficient to calculate the corresponding diurnal tidal current. The irregular shoreline has no apparent influence on the currents five miles offshore.

Results are shown in Figure 5 for a similar calculation of the currents observed by the U. S. S. *Long Island* in Feb.–May 1919 off the South Carolina coast in 32°42'.0 N, 79°06'.3 W. In this case the longshore components of the velocity compare poorly with the observed values [*Haight*, 1942; *U. S. Coast and Geodetic Survey*, 1956b]. The tide in this region is strongly influenced by the effect of friction, and the present theory cannot be expected to be strictly applicable under such circumstance.

Conclusions—A method is derived whereby an approximate distribution of the tide and tidal current in any offshore region where the effects of friction are unimportant can be computed from the known tides at adjacent shore stations. Solutions to the tidal differential equations are obtained to any desired accuracy by expanding the dependent variables in Maclaurin's series and by equating coefficients of equal powers of the independent space variables. The accuracy of the

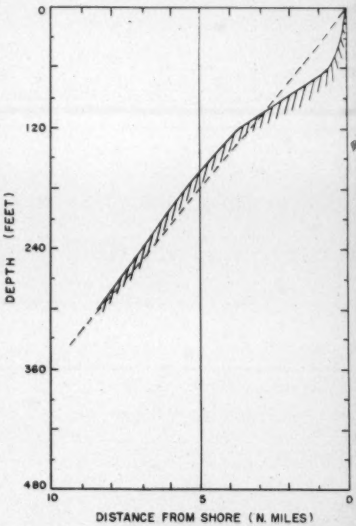

FIG. 3 — Bottom profile in the vicinity of the Umatilla Reef Light Vessel.

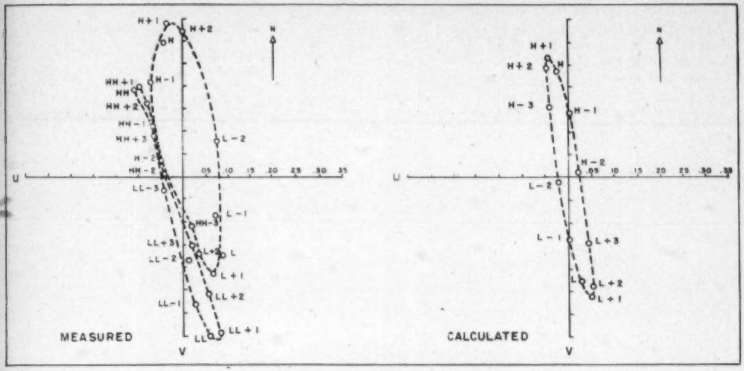

FIG. 4 — Comparison of calculated and measured tidal currents at the Umatilla Reef Light Vessel; velocities are in knots and times of tide are for Astoria

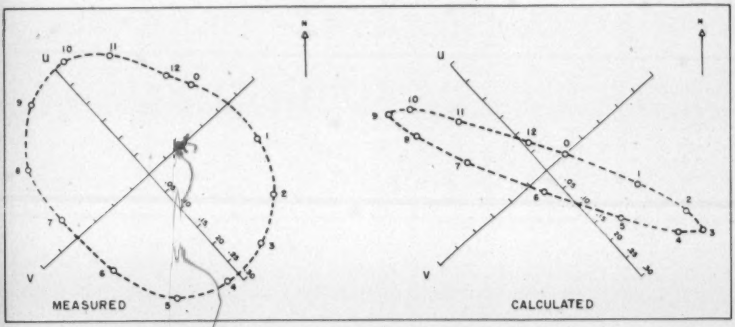

FIG. 5 — Comparison of calculated and measured tidal currents at the lightship U.S.S. *Long Island*; velocities are in knots and times are in hours after the Moon's Greenwich transit

method will depend on the regularity of the depth contours and on the availability of sufficient tidal data along the coastline. Modifications of this general approach are possible for special conditions. The first term in the expansion for depth must always be large compared to higher-order terms so that the final series converges with sufficient rapidity.

An example is given to illustrate the application of the method to the determination of the mean semidiurnal tidal currents at Umatilla Reef Light Vessel off the Washington coast.

Acknowledgment—This paper represents results of work carried out by the Department of Oceanography of the University of Washington under Contract N8onr-520/III, Project 083-012 with the Office of Naval Research.

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Direct Shear Stresses and Air Velocity Profiles on a Mechanical Wave Boundary

G. H. Moore and A. D. K. Laird

Abstract—Shear stresses of air on a rubber-sheet mechanical model of standing waves, stationary waves, and flat surface were measured directly and calculated from velocity profiles. Shear stresses varied as the 1.64 power of the main stream velocity and were less for the standing than for the stationary waves. The roughness length parameter was independent of the position on the surface and of the main stream velocity.

Introduction—An important problem yet unsolved in the flow of one immiscible fluid over another is the manner in which a wave system is established on an initially calm interface. This problem is of interest in meteorology for understanding the behavior of ocean waves under the influence of the winds, and is closely related to those of the many flow conditions encountered in the simultaneous flow of gas and liquid. A large obstacle in the path of investigators has been the lack of information on the velocity distributions and drag force at the interface of the fluids.

On natural interfaces a change of one wave characteristic usually changes all the others so that a systematic variation of the important wave parameters is impractical. Consequently, a model study is indicated wherein one of the fluids is replaced by a solid boundary which can be moved to simulate the surface of the interfacial wave and in which each parameter can be varied independently.

In the present investigation direct measurements of surface shear stress and velocity profiles were obtained on a mechanical model consisting of a rubber standing wave surface. In addition, shear stress and velocity profile measurements were obtained with the model surface at rest in the flat position and at rest in the maximum amplitude position corresponding to stationary waves. Surface shear stress was computed from the logarithmic distribution of the velocity profiles by use of the von Karman and Prandtl logarithmic theory, and a comparison was made with the values obtained by direct measurement.

Apparatus and procedure—The experimental work was performed in an open circuit, closed test section rectangular wind tunnel 12 ft long, 1.25 ft high, and 2.02 ft wide. The air was sucked through the tunnel by a centrifugal fan driven by a 5-hp motor. The bell-shaped entrance of the tunnel was covered with three 18-mesh wire screens. The walls of the tunnel were of A-grade plywood painted with semi-gloss enamel. The floor and roof were of aluminum sheeting. The leading edge of the model was five feet from the downstream end of the entrance bell.

The model surface was of 0.012-inch thick rubber dental dam stapled to pine slats set on half-inch centers. Alternate slats were attached to pairs of bars driven by eccentrics and spur gears connected to a $\frac{1}{4}$-hp, 1800-rpm synchronous motor, so that alternate slats were 180° out of phase. Figures 1 and 2 show the model with flat surface and with stationary waves.

The model rested on three floats in three drums of water. The float elevation could be controlled by water inlet and outlet valves. By these controls the mean model surface was leveled by eye with the floor of the channel. Four slack thin horizontal wires prevented the model from touching the walls. The lower portion of the model was inclosed by a vacuum box. A 4-inch diameter stove pipe connected the vacuum box to a downstream portion of the channel to equalize the pressure above and below the rubber model surface.

The Pitot impact tube was 1.5 inches long with 0.025-inch inside diameter and 0.042-inch outside diameter. The impact tube was connected to a depth gage (least count 0.001 ft) which was set at a convenient reading when the probe was just touching the mean model surface. Six positions for the impact tube were located along the channel roof parallel to the airflow, and another four positions were located transverse to the airflow over the center of the test section. These latter positions were used to establish the horizontal velocity distribution of the channel. A series of six static taps was located 4.5 inches above the channel floor and placed such that they would be in line with the end of the impact tube probe. Velocity traverses were taken for five positions of the impact tube for each of the three surface conditions.

A torsion balance was used to measure the total

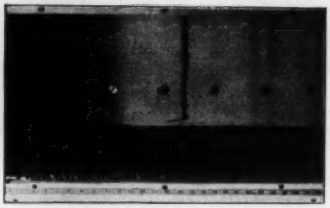

FIG. 1 — Test section; model surface flat

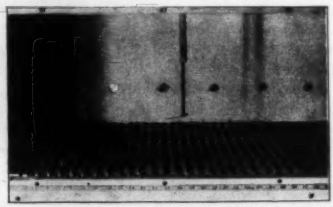

FIG. 2 — Test section; model surface as stationary waves

drag force on the model surface. The balance was connected directly to the model by means of strong sewing thread. Total drag force measurements were taken for the three model surface conditions for various values of midstream velocity.

The velocity head was indicated by an inclined Ellison draft gage (least count 0.005-inch of water), the range of which was 0.5 inch water. The airspeed was controlled by adjusting the cross sectional area of the channel at the outlet.

Results and discussion—The logarithmic theory of *von Karman* [1930] and *Prandtl* [1932] shows the relation between air velocity and the distance from a surface within a turbulent boundary to be

$$u = \frac{2.3\sqrt{\tau_y/\rho}}{\kappa} \log \frac{z}{z_0} \qquad (1)$$

where

- u = time average of air velocity, ft/sec
- z = height above the mean model surface, ft
- z_0 = roughness length parameter, ft, assumed to be very much less than z
- τ_y = shear stress on the model surface determined by logarithmic computation from a velocity profile, lb/ft²
- κ = universal constant
- ρ = mass density of the air, lb sec²/ft⁴

The value of 0.393 for the universal constant was used in this investigation for the three conditions of the model surface. This value of κ was determined empirically by *Schlichting* [1955] for the case of the flat plate. The variable $\sqrt{\tau_y/\rho}$ is called the friction velocity and is represented by u_*.

Eq. (1) may be rewritten as

$$u = a \log z + b \qquad (2)$$

where the constants a and b can be determined from the linear portions of the velocity profiles plotted on semi-log paper. Representative velocity profiles are shown in Figure 3. However, to eliminate personal error these constants were determined by the least-mean-square method of calculating equations from experimental points. The experimental points deviated from the logarithmic velocity curve within 0.015 ft of the model surface. However, the viscous shear stress which was neglected in the derivation of (1) becomes important for very small values of z. The measured boundary layer thickness of the air varied from 0.07 ft over the aluminum sheet to 0.30 ft over the model at its trailing edge.

From (1) and (2) a value of u_* was determined from each velocity profile for the various locations

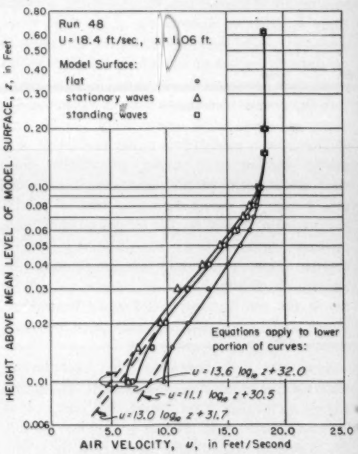

FIG. 3 — Height above mean level of model surface as a function of air velocity with model surface condition as parameter; distance from leading edge of model, x, equals 1.06 ft; midstream velocity, U, equals 18.4 ft/sec.

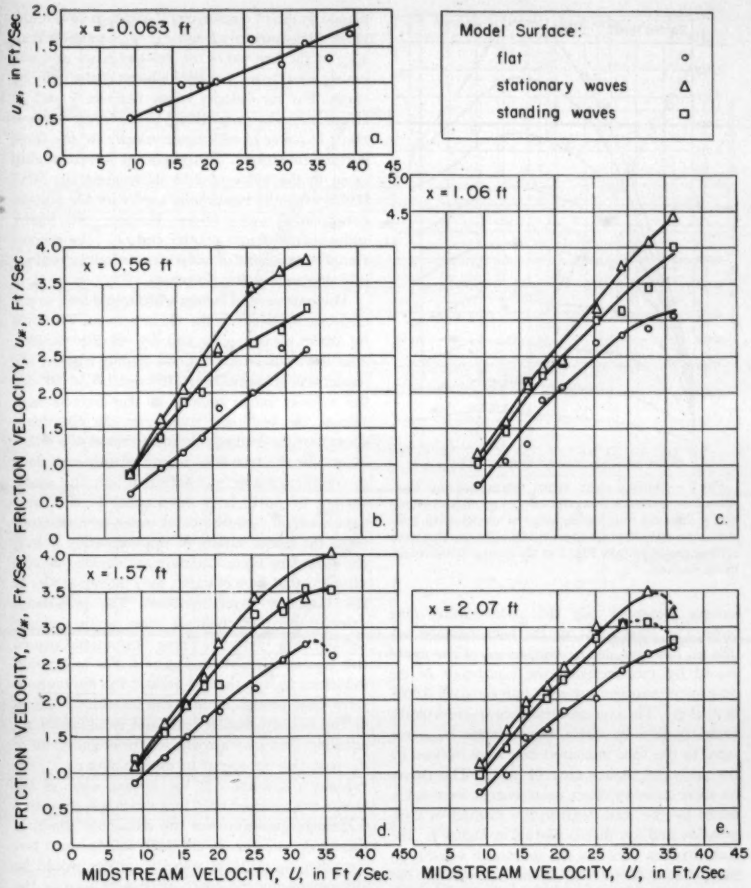

FIG. 4—Friction velocity as a function of midstream velocity (a) for aluminum sheet surface; (bcde) with model surface condition as a parameter

on the model surface and was plotted as a function of midstream velocity in Figure 4. A crossplot of Figure 4 giving τ_V as a function of position on the model surface is shown for the surface condition of standing waves in Figure 5 (air density 0.075 lb/ft^3).

The area under each of these latter curves divided by the length in feet of the model represents the average surface shear stress on the model $\tau_{V_{av}}$ and is shown plotted as a function of midstream velocity in Figure 6 for the three model surface conditions.

Since all drag force measurements were taken with the model centered in the test section, the

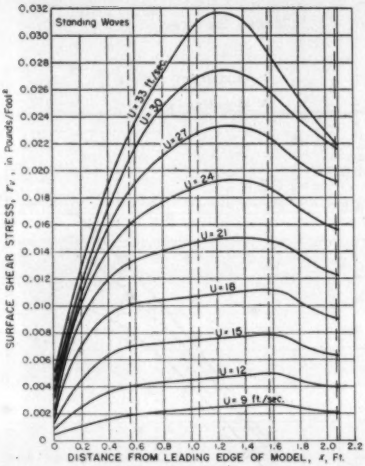

FIG. 5 — Surface shear stress determined by logarithmic computation from the velocity profiles as a function of distance from leading edge of model with midstream velocity as parameter; model with standing wave surface; crossplot from Fig. 4 at the quarter points of the model surface.

balance measured only the model surface drag force. The least count of the force balance was 0.05 gr; however, due to fluctuations of the model caused by measurement, the inaccuracy of the drag force measurement was approximately 0.0005 lb (0.25 gr). The average surface shear stress on the model surface by direct measurement $\tau_{D_{av}}$ was equal to the total measured drag force divided by the projected surface area (4.18 ft²). The curves for shear stress by direct measurement were determined by the least-mean-square method of computation and are shown plotted in Figure 6. The shear stresses varied as the midstream velocity to the power 1.66 for the model flat surface and stationary waves, and 1.60 for the model standing waves. The shear stress on the stationary and the standing waves was up to 1.5 times that for the flat surface which was some 3.7 times that for the aluminum sheet. The shear stress for the standing waves, however, for the chosen frequency of 8.57 cycles per second was some five per cent less than that for the stationary waves.

The shear stresses obtained from the velocity profiles are only in fair agreement with those obtained by direct measurement. For each case of the three model surface conditions, $\tau_{V_{av}}$ was lower than $\tau_{D_{av}}$ at the low end of the velocity range and was nearly equal to $\tau_{D_{av}}$ at the high end of the velocity range. For the velocity range between 9 and 20 ft/sec, $\tau_{V_{av}}$ was proportional to an average value of the 2.13 power of midstream velocity for the three surface conditions. This exponent is remarkably close to the value of 2.15 determined by *Sibul* [1955] using the logarithmic theory for the surface condition of water waves. However, for higher values of midstream velocity and $\tau_{V_{av}}$, the proportionality exponent of midstream velocity continually decreases as $\tau_{V_{av}}$ increases.

There are several factors which could lead to the discrepancy between the shear stresses obtained by direct measurement and by velocity profiles. The Reynolds number at the leading edge of the model was between 2.7×10^5 and 1.0×10^6 for the velocity range covered in this investigation. Hence, the boundary layer over the aluminum sheet near the leading edge of the model was either in or near the transition region of turbulent flow. A transition region was indicated over the model surface by fairly large fluctuations in the draft gage readings, ± 0.03 inch of water, at a distance from the model surface of approximately $\frac{1}{2}$ to $\frac{3}{4}$ the boundary layer thickness and smaller fluctuations, ± 0.01 inch of water, over the remainder of the boundary layer thickness. The midstream velocity head fluctuations were approximately ± 0.001 inch of water. These fluctuations caused the scatter of points in Figure 4. For midstream velocities higher than 33 ft/sec, the fluctuations were large enough so that the logarithmic slopes of the velocity profiles could not be obtained accurately. This may account for the dropping off of u_* past this air speed. In determining $\tau_{V_{av}}$, the velocity distribution at the leading edge of the model was assumed to be that which was measured 0.75 inch upstream over the aluminum sheet. If the static pressure in the duct and vacuum box were not equal, these velocity profiles would be altered crossing the $\frac{1}{4}$-inch air gap in front of the leading edge of the model. However, this differential in pressure was practically zero. In determining $\tau_{V_{av}}$, it was assumed that the horizontal velocity distribution was constant for each height above the model surface. This assumption seemed reasonable since several horizontal velocity traverses at various air speeds showed the boundary layer along the duct walls to be approximately 0.15 ft while the duct width was 2.02 ft. It is questionable

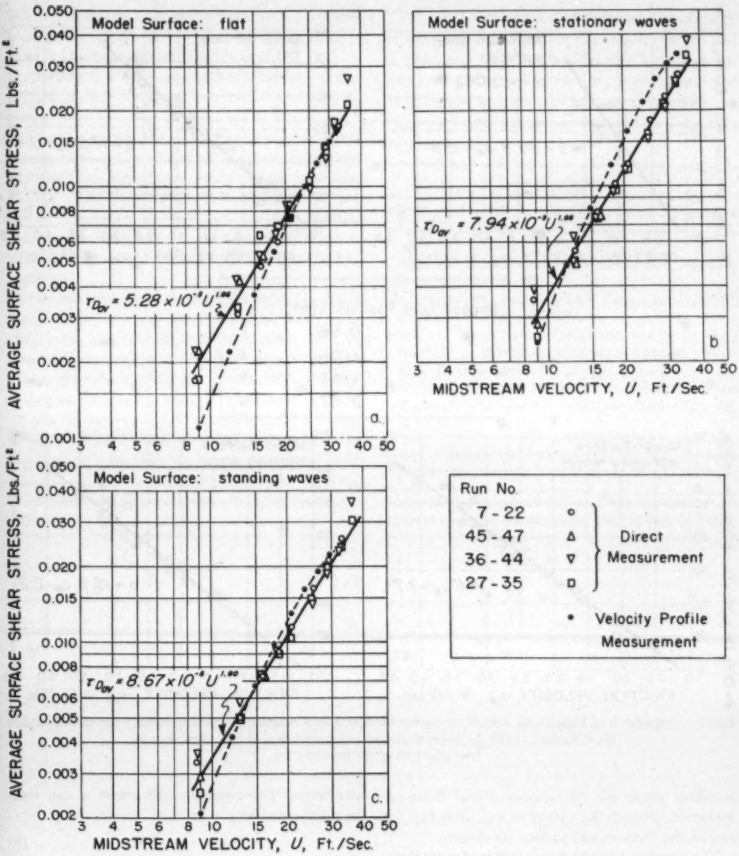

FIG. 6—Average surface shear stress as a function of midstream velocity by the methods of direct measurement and logarithmic computation from the velocity profiles for the three model surface conditions

that four velocity profiles over the model surface were enough to establish accurately the shear stress distribution along the model surface, as shown in Figure 5. It does, however, suffice to form a rough comparison between the shear stresses determined by the logarithmic computation from the velocity profiles and by direct measurement.

Modification of the universal constant κ results in multiplying the shear stresses by a constant factor. This would result in shifting the curves of $\tau_{V_{av}}$ in Figure 6 to a higher or lower position. Closer correlation between $\tau_{V_{av}}$ and $\tau_{D_{av}}$ would result if a value for κ of 0.43 were used for the flat surface and a value for κ of 0.37 were used for the stationary waves. No change in κ for the standing waves would be needed. However, this method

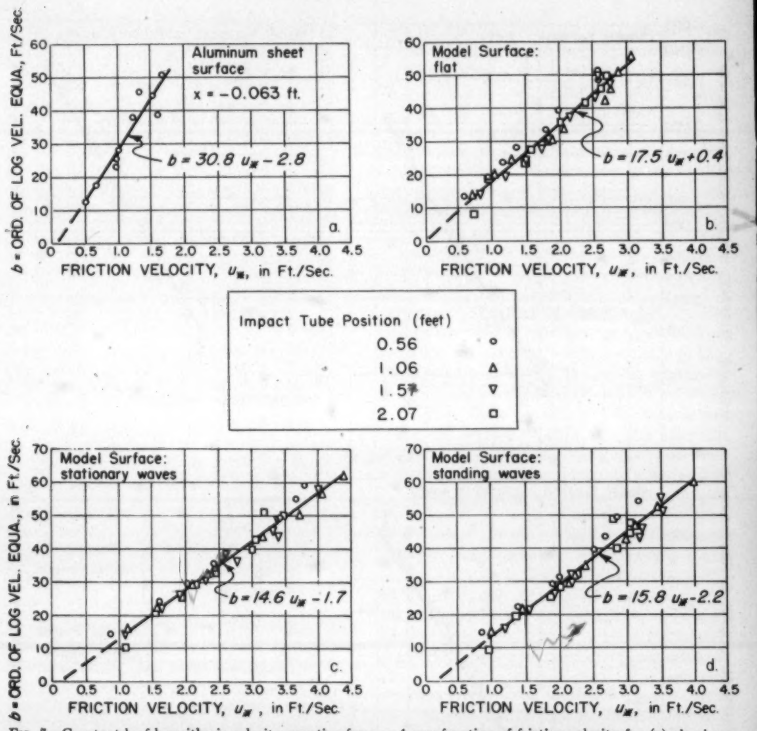

FIG. 7—Constant b of logarithmic velocity equation for $z = 1$ as a function of friction velocity for (a) aluminum sheet surface; (bcd) the three model surface conditions; values are shown for four positions of the impact tube

is rather crude for no value of κ will cause coincidence between the curves of $\tau_{V_{av}}$ and $\tau_{D_{av}}$ for any of the three model surface conditions.

The roughness length parameter is of some interest. To determine this parameter, the constant b of (2) was plotted as a function of u_* for the three conditions of the model surface in addition to that of the aluminum sheet, as shown in Figure 7. From the plotted points it was assumed that the constant b varied linearly with u_*. The equations for these curves were determined by the least-mean-square method of computation. In each case the intercept on the b-axis was near zero and was assumed zero to determine the roughness length parameter. The roughness parameter z_0 can then be represented by

$$\log z_0 = -c/5.85 \qquad (3)$$

where the constant c is the slope of the b versus u_* plot. By use of (3) the roughness length parameters were found to be 0.000005 ft, 0.0010 ft, 0.0032 ft, and 0.0020 ft for the surface conditions of the aluminum sheet, model flat surface, stationary waves, and standing waves, respectively. *Motzfeld* [1937] found that for sharp-crested rigid waves the roughness length parameter, z_0, was proportional to the wave height H with the following relationship

$$z_0 = H/7./25 \qquad (4)$$

For the model wave height of 0.200 inch, (4) yields a roughness length parameter of 0.0023 ft which is near the value obtained experimentally.

Conclusions—The most accurate method of obtaining surface shear stress is by direct measurements.

There was fair agreement between the shear stresses obtained by direct measurement and those obtained by logarithmic computation from the velocity profiles using a value of 0.393 for the universal constant on a flat plate. However, modification of the universal constant improved the correlation between shear stresses obtained by the two methods.

The surface shear stresses obtained by direct measurement for the three model surface conditions were proportional to approximately the 1.64 power of midstream air velocity, whereas for the shear stresses obtained by logarithmic computation from the velocity profiles, the exponent of midstream velocity varied between 1.0 and 2.3 for the velocity range covered in this investigation. The shear stresses for standing waves were found to be less than those for stationary waves of the same amplitude for the frequency of 8.57 cycles per second.

The roughness length parameter was found to be independent of position on the model surface and of midstream air velocity. Motzfeld's relation for determining the roughness length parameter for sharp-crested waves was in fair agreement with the roughness length parameter obtained for the model stationary waves.

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Flooded Quarries for Experimental Work*

MILTON S. RUTSTEIN

Abstract—Flooded quarries have some technical and economic advantages for underwater experimental work and for testing oceanographic equipment, particularly where explosions are involved or where wave action must be minimized. The quarries visited in and near New England are described.

Introduction—In the course of underwater-sound work at the Woods Hole Oceanographic Institution, there developed a need for a body of water for short-range experiments using explosives. Ponds, lakes, and rivers were not suitable because of size, depth, or the impracticality of using explosives even though the damaging effects of explosives on fish are over-rated. This particular experiment required that the body of water should be at least 300 ft long, 100 ft wide, and 75 ft deep; by far the most difficult requirement was that the quarry be sufficiently removed from houses so that the explosives would not cause any annoyance or physical damage to the local community.

An abandoned flooded quarry satisfying these requirements was selected and used during the summers of 1954 and 1955. This quarry was the Blackington Farm quarry owned by the Rockland-Rockport Lime Company of Rockland, Maine. During the course of several months of testing, there was ample opportunity to appreciate the convenience of a land base and the relative stability of water conditions. The sides of the quarry were so steep that there was 90 ft of water under the end of a small cantilever platform ten feet from the edge.

A quarry is, of course, no substitute for the ocean, but certain aspects of some problems or of instrument development can be studied or tried out without the use of a ship. A land base provides an economic and convenient means for repeating experiments without the hindering influence of high seas or bad weather.

Scientific and Engineering Uses of Quarries

In considering uses for quarries, points to keep in mind are the accessibility, the calm water surface, and the ease of handling equipment. Abandoned quarries will seldom have electrical power convenient. Suggested uses for quarries are listed as follows:

Explosive research—Some experiments in high explosive research can be handled nicely in quarries. The walls or banks of the flooded holes are usually high enough so that a grid of wires may be stretched across the quarries. This will allow explosives to be lowered to various depths at specific ranges from receiving instruments, and measurements of underwater sound and explosive intensities may be made.

For this type of work quarries that are privately owned have many advantages over those that are not. This involves dealing with fewer people and reduces the amount of negotiations necessary to shoot explosives near a community. Moderate remoteness is essential. For example, at one mile 10 pounds of TNT should do no damage, but it might bother some people.

Underwater sound—There are good opportunities for experimental work in this direction. During the summer months, sharp thermal gradients exist, and the quarries are often large enough to provide 30 milliseconds before any echos return.

Mixing problems—Wind exposure is usually less than with large lakes or ponds, resulting in relatively quiet surface water and nearly motionless bottom water. High quarry walls reduce the effects of wind on the water [*Stommel*, 1952].

Pressure testing—Large apparatus can be tested. At Tilley Foster Mine in Brewster, N. Y., there is a water-filled hole believed to be somewhat deeper than 600 ft. If so, it is possible to test equipment within 40 miles of New York City at a steady pressure equivalent to that along the continental shelf at the 100 fathom line.

Figure 1 is a map of New England showing the locations of the various quarries that were inspected. The principal quarries visited are listed in Table 1. A good many of these quarries are remote enough to allow the use of small explosive charges.

A useful guide for anyone beginning a search for

* Contribution No. 866 from the Woods Hole Oceanographic Institution.

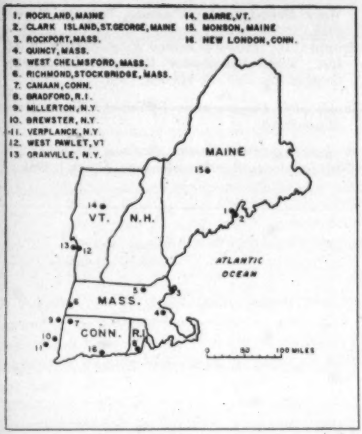

FIG. 1 — Map showing quarries investigated

flooded quarries is a list of kinds of quarries where operations are being or have been carried out, such as those in *Dale* [1923a, b], *Chute* [unpublished], and *Trefethen* [1953].

For those who are elsewhere and have different requirements, it is recommended that they contact the U. S. Geological Survey, the State Geologist, or the geological department of a nearby university.

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The author and his co-workers are particularly indebted to the Rockland-Rockport Lime Co. and to their officers for the use of their property and for their enthusiastic cooperation to make our quarry work a success.

TABLE 1 — *Principal quarries visited*

Map key	Name of quarry	Length[a] & Breadth[a]	Depth[a]	Remoteness from houses[a]	Accessibility by roads	Purpose
8	Crumb	300 × 150	50–140	500	Good	Granite
8	Klondike 1	200 × 125	100?	one house 500	Good	Granite
8	Klondike 2	300–500 × 200	100?	one house 500	Good	Granite
7	Lawrence	300 × 200	60	2600	Good	Limestone
10	Tilley Foster	600 × 300	600?	700	Good	Iron Ore
11	Verplanck	1000 × 400	70	800	Good	Limestone
9	Mulby's Ore Body	300 × 250	100?	650	Good	Iron Ore
12	Rising-Nelson Slate	Several various dimensions	75?	2600	Good	Slate
13	Briar Hill	Several various dimensions	same	2600	Good	Slate
14	Canton	350 × 250	90	800	Good	Granite
15	Hebron Pit	250 × 75	400?	500	Good	Slate
1	Blackington Farm	600 × 120	180	800	Good	Lime
16	Bottinelli	300 × 200	50	...	Good	Granite
4	Quincy (five)	300 × 100–200	100?	650	Good	Granite
3	Rockport 1	500 × 350	90	2600	Good	Granite
	Rockport 2	300 × 200	50	500	Good	Granite
2	Clark Island	300 × 125	75?	5100	Poor; road is brushed in	Granite

[a] Dimensions in feet (approximate).

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A Probe for Measurement of Thermal Conductivity of Frozen Soils in Place

ARTHUR H. LACHENBRUCH

Abstract—A probe has been used for several hundred determinations *in situ* of the thermal conductivity of naturally frozen and thawed soils, snow, fresh-water ice, and sea ice in northern Alaska. The probe is about 20 inches long, one-quarter inch in diameter, and contains a small bead thermistor that is used as the temperature-sensitive element. Under normal field conditions conductivity determined with the probe is reproducible within about two per cent. The absolute accuracy of the instrument is estimated to be within five per cent. Results obtained with this probe have suggested a modification in design that is expected to offer a practical method for determining simultaneously the thermal conductivity and thermal diffusivity *in situ*.

Introduction—In recent years several investigators of the thermal conductivity of nonmetallic substances have used the transient-probe method because it gives a high degree of accuracy with equipment that is easy and inexpensive to construct and sufficiently mobile to be ideally suited for measurements in the field.

In its general form the probe consists of a tube sealed at one end, an axial heater filament, and a temperature-sensitive element placed about midway on the long axis of the tube [*Hooper* and *Lepper*, 1950]. The probe is inserted into a hole bored in the test medium and a constant amount of current is passed continuously through the filament. The temperature increase, as indicated by the probe's temperature element, is recorded as a function of time after the start of heat generation. From these data, the thermal conductivity of the medium is computed.

The following symbols are used in this paper:

Θ	temperature increase, °C
t	time since start of heat generation, sec
t_0	time correction constant, sec
t'	$= t + t_0$
K	thermal conductivity of test medium, cal/cm °C sec
c	volume specific heat of test medium, cal/cm³ °C
α	thermal diffusivity of test medium $= K/c$, cm²/sec
c_0	mean volume specific heat of probe, cal/cm³ °C
q	rate of heat generation per unit length, cal/cm sec
a	distance of point of temperature measurement from axis, cm
$\ln \gamma$	Euler's constant (0.5772)
A	$\frac{1}{2}c_0/c$
S	$= 2A - 1$
$J_n(x)$	Bessel function of the first kind of order n
$Y_n(x)$	Bessel function of the second kind of order n
η	$= a^2/\alpha t$

Simple theory of the probe method—Because the theory of operation of the probe has been discussed [*D'Eustachio* and *Schreiner*, 1952; *Hooper* and *Lepper*, 1950; *Van der Held* and *Van Drunen*, 1949; *Buettner*, 1955] only a simple outline necessary to an understanding of the application is presented here. Certain refinements of the theory are discussed in a later section.

As a first approximation, the temperature disturbance Θ, resulting from heat introduced by the probe is identified with that which would be produced by a continuous linear heat source of constant strength embedded in an infinite homogeneous medium. The solution to this problem is given by *Carslaw* and *Jaeger* [1947, p. 221].

$$\Theta(a,t) = \frac{q}{4\pi K}\int_{a^2/4\alpha t}^{\infty} e^{-u}\frac{du}{u}$$

$$= \frac{q}{4\pi K}\left\{\ln\frac{4\alpha}{\gamma a^2} + \ln t + \frac{1}{1\cdot 1!}\frac{a^2}{4\alpha t} - \frac{1}{2\cdot 2!}\left(\frac{a^2}{4\alpha t}\right)^2 + \cdots\right\} \qquad (1)$$

For temperature measurements taken near the heat source (value of a is small), the powers of $a^2/4\alpha t$ may be neglected after relatively short times and we obtain

$$\Theta \approx \frac{q}{4\pi K}\ln t + \text{constant}, \quad t >> \frac{a^2}{4\alpha} \qquad (2)$$

Thus for sufficiently large t, a graph of Θ versus $\log t$ should yield a straight line of slope $q/4\pi K$. The value of q is computed from the current and resistance of the heater filament, so K can be determined from the slope read from such a graph.

From (1) and (2) it follows that if the heat generation is allowed to persist for $0 < t < s$, $s >> a^2/4\alpha$, then the subsequent cooling can be

described by adding to (1), the corresponding solution for a linear source of strength $-q$ starting at $t = s$. Hence

$$\Theta = \frac{q}{4\pi K}\int_{a^2/4\alpha t}^{\infty} e^{-u}\frac{du}{u} - \frac{q}{4\pi K}\int_{a^2/4\alpha(t-s)}^{\infty} e^{-u}\frac{du}{u}, \quad t > s$$

$$\approx \frac{q}{4\pi K}\ln\frac{t}{t-s}, \quad (t-s) >> \frac{a^2}{4\alpha} \qquad (3)$$

Thus recording the manner in which the probe returns to equilibrium after the cessation of heat generation should give a second set of data from which the conductivity can be determined.

This simple theory does not account for the finite dimensions of the probe or for the difference in the thermal properties of the probe materials and the test medium. The finite length of the probe will introduce departures from (1) for large values of time as a result of the development of longitudinal thermal gradients. The finite radius of the probe results in discrepancies for short values of time arising from the difference in properties of the probe and test medium, and the finite distance a of the sensing element from the source. If the probe is sufficiently long, the departures from (2) introduced by combined radial effects will die out and the logarithmic relationship will ultimately obtain. This may be explained qualitatively by noting that after an initial stage of rapid warming, the heat leaving the probe is approximately equal to that being liberated within it. After this period, the effects of contrast in thermal properties and of the small value of a become unimportant. *Van der Held* and *Van Drunen* [1949] and subsequent workers have attempted to compensate for these effects by adjusting the time origin in (2) by a constant amount t_0 depending on the dimensions of the probe and the thermal properties of the probe materials and the test medium.

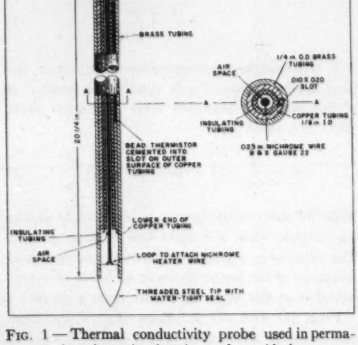
HEATER LEADS TO 6-VOLT D-C SUPPLY
THERMISTOR LEADS TO WHEATSTONE BRIDGE
TENSION SUPPORT FOR NICHROME HEATER WIRE
MICARTA
BRASS CROSS PIECE
BRASS TUBING
AIR SPACE
1/4 in. O.D. BRASS TUBING
.040 X .020 SLOT
A
A
COPPER TUBING 1/8 in. I.D.
INSULATING TUBING
.025 in. NICHROME WIRE B & S GAUGE 32
BEAD THERMISTOR CEMENTED INTO SLOT ON OUTER SURFACE OF COPPER TUBING
20 1/4 in.
LOWER END OF COPPER TUBING
INSULATING TUBING
AIR SPACE
LOOP TO ATTACH NICHROME HEATER WIRE
THREADED STEEL TIP WITH WATER-TIGHT SEAL

FIG. 1 — Thermal conductivity probe used in permafrost investigations in northern Alaska

Description of the probe used in permafrost studies in Alaska—The probe described below was designed and built during the winter of 1952–1953 at Barrow, Alaska. Since that time it has been used for more than 400 determinations *in situ* of the thermal conductivity of frozen and thawed soil materials including peat, clay, silt, sand, and gravel. Snow, fresh-water ice, and sea ice also were tested.

A drawing of the probe is shown in Figure 1. The electrical resistance thermometer used is a small bead thermistor (0.014 inch in diameter) with a negative temperature coefficient of resistance of roughly four per cent per degree C in the range from +20°C to −20°C and a total resistance of about 5000 ohms at 0°C. Such a thermistor is ideally suited for this use because of its small size, high sensitivity to small changes in temperature, and the fact that it does not require a reference junction as do thermocouples. The inner copper tube was inserted to reduce radial and longitudinal thermal gradients within the probe and to give added strength. The copper tube was made shorter than the enclosing brass tube to reduce end losses. The brass cross piece attached to the brass tube near the upper end of the probe receives a special wrench by means of which the probe can be removed without damage if it should become frozen into the test medium.

Procedure for field use of the probe—A pit is dug in the ground and a hole bored horizontally into the stratum to be tested. In thawed media and frozen gravels, the hole is made by driving a steel rod 24 inches long, and one-quarter inch in diameter. In frozen media other than gravels, the hole is bored with a carpenter's brace and an electrician's bit 24 inches long, and one-quarter inch in diameter. For use in frozen media, the probe, driving rod, and the electrician's bit are coated with low-temperature silicone grease to eliminate

the possibility of their freezing in place and to reduce contact resistance. The probe is then forced into the hole and its temperature, as indicated by the thermistor within it, is read periodically until the rate of change becomes constant. This constant rate of change is recorded as the temperature drift of the medium.

To insure that the heater current has the desired value from the start of the test, a test coil with the same resistance as the probe heater is connected in the circuit before the test and the initial current adjustment is made. A constant flow of electric current is then passed through the axial heater wire for 15 to 20 or more minutes. During this period recordings are made of the thermistor resistance as a function of time at intervals of about one minute. Care must be taken that the temperature does not rise to the point at which an appreciable amount of latent heat is liberated by the melting of interstitial ice.

The heater current used for a particular test is generally between one and two amperes (thus $0.008 < q < 0.033$ cal per cm sec), depending upon the anticipated conductivity of the test medium. It is supplied by six-volt storage batteries, and controlled manually to within 0.01 ampere with variable resistors. The thermistor resistance measurements are made to the nearest ohm with a modified four-dial Wheatstone bridge and the time is measured to within one second with a stop watch.

After the heater current is turned off, temperature-time observations may be continued to give the cooling data to which (3) can be applied for a second determination of the conductivity.

Method of analyzing the data—Results of a test made in frozen gravel fill at Barrow, Alaska, are presented to illustrate the method of handling the data.

First, the thermistor resistances are converted to temperatures and the small correction for ambient drift applied. The corrected temperatures are then plotted against the logarithm of time after the start of heat generation. It is seen from Figure 2 that such a series of points defines a curve that seems asymptotically to approach a straight line as predicted by the simple theory. In plots of this kind relatively few closely spaced points follow the linear relationship and we have some leeway in drawing the straight line joining them. An unknown error is introduced by identifying the slope of such a line (Curve A, Fig. 2) with the slope of the asymptote. As pointed out above,

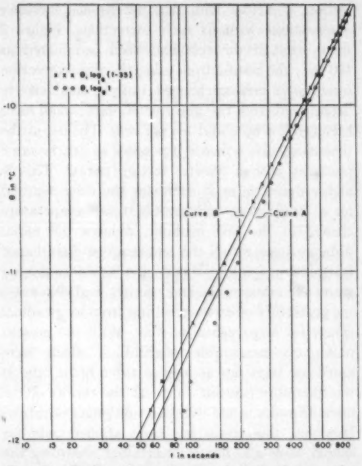

FIG. 2—Probe temperatures during the warming period of conductivity test on frozen gravel, with and without time correction

Van der Held and *Van Drunen* [1949] have shown that the linear relationship can be obtained for smaller values of time by replacing the variable t by $t' = t + t_0$, where t_0 is a constant depending on the dimensions of the probe, and the thermal properties of the probe and test medium. The theoretical prediction of t_0 is a tedious and uncertain process. However with certain precautions t_0 can be determined quickly by trial and error, as the value that brings the largest number of points of the graph of Θ versus $\log (t + t_0)$ on to the straight line determined for larger values of time. With the present probe and gravels of the type under discussion $t_0 \approx -35$ sec. The crosses in Figure 2 represent a plot of temperature versus $\log (t - 35)$. The slope of the straight line B, determined by the latter points of this plot, is identified with the quantity $q/4\pi K$, from which we obtain a conductivity of 1.93 millical per °C cm sec. (For this test $q = 0.0212$ cal per cm sec.) Curve A, drawn from data without the time correction, gives a conductivity of 1.86 millical per °C cm sec. This represents a discrepancy of about four per cent, somewhat greater than the reproducibility of results.

When longer tests are run the straight line determined for early observations, using the time cor-

rection, coincides with that determined for later observations without such corrections. Figure 2 shows that if the test had been terminated at 400 sec., the results from using the time correction would have been unchanged, but the conductivity determined from the uncorrected data would have been too low by about ten per cent. The use of the time correction t_0 makes it possible to get the same precision with a shorter testing period. This is highly desirable as it decreases the time required for a single test, reduces the total temperature change in the test medium, reduces the radial distance over which the temperature disturbance is significant (making it possible to consider thinner strata as homogeneous and infinite), and eliminates the possibility of errors resulting from longitudinal effects for large values of time. With the present probe, no measurable longitudinal effects were noted for tests run as long as three hours, and it was therefore possible to check the results of the usual 15-minute test with tests of longer duration. However, this check has been applied only for special cases and hence uncertainty regarding the general absolute accuracy of the probe method will remain until the theoretical significance of t_0 is understood.

In Figure 3 the cooling data are presented as a

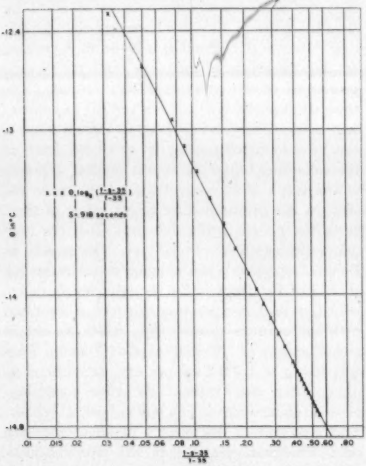

FIG. 3 — Probe temperatures during the cooling period of conductivity test on frozen gravel with the time correction.

graph of temperature versus log $[(t - s - 35)/(t - 35)]$ in accordance with (3). The slope of the straight line indicated for larger values of time gives $K = 1.92$ millical per °C cm sec. This is not significantly different from the value of 1.93 obtained from the data taken during the warming period. The agreement is not always this good, however, and it is generally found that conductivities determined from the cooling data are less reliable than those obtained from data taken during the warming cycle.

Test results indicate that under normal field conditions, conductivities determined with the probe described are reproducible to within about two per cent. This is less than the normal variation of conductivity within a single stratum for many of the materials tested. The absolute accuracy of the measurements can be checked roughly for special cases by comparison with results of other workers. Conductivities of lake ice determined with the probe agree to within about five per cent with the usually accepted laboratory determinations for pure ice [*Jacob* and *Erk*, 1929]. Slight variations in the natural conditions of the lake ice obviate a more precise estimate of the absolute accuracy by such a comparison. Probe tests on supersaturated bog peats containing more than 95 pct water by weight yield conductivities within five per cent of those tabulated for pure water at the same temperature.

Refinements of the probe theory—Van der Held and *Van Drunen* [1949] have pointed out that differentiation of (2) leads to

$$\frac{\partial t}{\partial \Theta} \approx \frac{4\pi K}{q} t \qquad (4)$$

and thus t_0 can be determined from the time intercept of a graph of $\partial t/\partial\Theta$ versus t. For larger probes this method has the disadvantage that the linear relation (4) generally does not obtain for small values of time, and for larger times the temperature changes very slowly, making $\partial t/\partial\Theta$ very sensitive to small errors in the measurement of temperature change. Thus, with the probe described above the method leads to an unsatisfactory spread of points and a highly uncertain value for t_0. Furthermore the procedure is tedious and it must be repeated for each medium tested. On the other hand the curve-fitting technique applied above provides a quick and simple method of determining t_0. However before it can be applied with assurance, theoretical justification of the procedure is required.

For most probes it is difficult to develop a refined

theory taking account of the contrast in thermal properties between the probe materials and the test medium, and the probe described above is no exception. There is one probe design, however, that seems particularly promising and this is discussed here because of its application to the understanding of the present probe and its possible value to other workers in this field.

If the thermistor were placed in a pit at the interface between two concentric tubes of highly conducting metal as in Figure 1, but the inside diameter of the inner metal tube were so small as to just allow space to receive the axial heater element, then the probe would be composed almost entirely of material with a conductivity on the order of 100 times that of the test media. In this case the behavior of the probe should be very closely approximated by the temperature rise in a perfectly conducting cylinder with constant internal heat generation, embedded in an infinite homogeneous medium. The solution to this problem, which has been discussed by *Buettner* [1955], follows from a result given by *Carslaw* and *Jaeger* [1947, p. 284, Eq. (18)]. In view of the probe design, there is no inconsistency in letting a, the radial coordinate of the thermistor, represent also the radius of the probe. Thus

$$\Theta(a, t) = \frac{2q}{\pi^3 K} \int_0^\infty \frac{1 - e^{-(\alpha t/a^2)x^2}}{\{[AxY_0(x) - Y_1(x)]^2 + [AxJ_0(x) - J_1(x)]^2\}\, x^3}\, dx \tag{5}$$

Thus the rate of temperature rise in the probe is given by

$$\frac{\partial \Theta}{\partial t} = \frac{2\alpha q}{a^2 \pi^3 K} \int_0^\infty \frac{e^{-(\alpha t/a^2)x^2}}{\{[AxY_0(x) - Y_1(x)]^2 + [AxJ_0(x) - J_1(x)]^2\}} \frac{dx}{x} \tag{6}$$

This integral has been used by *Bullard* [1954] in connection with a slightly different problem.

It can be shown that the denominator of the integrand in (6) has no zeroes. Therefore, for sufficiently large values of t, only small values of x result in appreciable contributions to the integral. Approximating the Bessel functions by their ascending series we obtain

$$\frac{\partial \Theta}{\partial t} = \frac{\alpha q}{2a^2 \pi K} \int_0^\infty x f(x) e^{-(\alpha t/a^2)x^2}\, dx$$

where

$$[f(x)]^{-1} = 1 + 2(A - \tfrac{1}{2})x^2 \ln \frac{\gamma x}{2} + \tfrac{1}{2} x^2 + (A - \tfrac{1}{2})^2 x^4 \left(\ln \frac{\gamma x}{2}\right)^2 - \tfrac{1}{8} x^4 \ln \frac{\gamma x}{2} + \left[\tfrac{1}{2}(A - \tfrac{1}{4}) + \frac{\pi^2}{4}(A - \tfrac{1}{2})^2\right] x^4 + O\left(A^2 x^6 \ln^2 \frac{\gamma x}{2}\right)$$

Expanding $f(x)$ in a Taylor series, integrating term by term and introducing the numerical value for $\log \gamma$ (Euler's constant) yields

$$\frac{\partial \Theta}{\partial t} = \frac{q}{4\pi K} \frac{1}{t} \{1 + \epsilon(\eta, S)\} \tag{7a}$$

where

$$\epsilon(\eta, S) = -\eta \ln \eta[\tfrac{1}{3}S] - \eta[\tfrac{1}{2} + 0.10S] + \eta^2(\ln \eta)^2[0.38S^2] + \eta^2 \log \eta[0.52S^2 + S + 0.13] + \eta^2[-0.91S^2 + 0.19S + 0.27] + O(S^3\eta^3 \ln^2 \eta) \tag{7b}$$

and ϵ represents the departure of the rate of temperature rise in the 'perfect conductor probe' from that predicted by the simple theory (2).

Thus a graph of temperature rise versus $\ln t$ will yield a straight line only for t sufficiently large that ϵ can be neglected. However for larger values of t we can replace t by $t' = t + t_0$ and adjust t_0 to compensate for ϵ (that is, we can select the value of t_0 which best satisfies the relation

$$1/(t + t_0) \approx (1/t)(1 + \epsilon)$$

or

$$t_0 \approx -t\epsilon, \qquad t >> t_0 \tag{8}$$

for the range of time over which the probe test data are to be used). Thus to obtain a straight line of slope $q/4\pi K$ on a graph of temperature versus $\ln (t + t_0)$ we must run the test long enough so that $\epsilon(\eta, S)$ is small throughout a substantial time interval. Within this time interval we may take the time correction as the average value of t_0 as defined by (8). It will be seen from (7b) that ϵ is sensitive to S and that longer tests are generally required when the contrast in specific heats is large and/or when the diffusivity is small. It is seen from (7ab) and (8) that when $S = 0$, $t_0 \approx +a^2/2\alpha$. For other values of S, t_0 can be estimated from (8) by numerical means.

Because of the slow convergence of the repre-

sentation (7b) for ϵ it would be desirable to have the function $\epsilon(\eta, S)$ or the integral in (6) tabulated numerically. A short table of the integral in (6) has been presented by *Bullard* [1954] but the range of variables is not satisfactory for the present purpose.

(Since this paper was written, J. C. Jaeger has published an article [*Australian J. Phys.*, **9**, 167–179, 1956] in which he presents a table which supplements Bullard's, but further extension is required for the present application. Jaeger's paper also discusses the present problem and includes a result equivalent to (7ab) to the second term in η. It was obtained from a result given by Blackwell [*J. Appl. Phys.*, **25**, 137–144, 1954] in an article previously unknown to the author. The reader is referred to Blackwell's work for a more complete treatment of the probe theory. The present discussion is adequate for our purpose.)

Note that t_0 depends upon c and K. Thus, making the reasonable assumption that contact resistance is negligible, with the perfect conductor probe it should be possible to determine t_0 and K by the curve-fitting technique applied in the last section, and from the value of t_0, to estimate the volume specific heat of the test medium from a table constructed from (8). Preliminary results suggest that with proper design, the method may lead to more accurate values for the volume specific heat than those obtained by direct field measurement of the bulk density and mass specific heat.

Approximately 75 pct of the present probe (Fig. 1) is composed of material that can be considered a perfect conductor. The remaining 25 pct in the axial region is occupied by poorly conducting air and insulating tubing. Applying (8) to the example given earlier ($S \approx 0.75$, $\alpha \approx 0.005$ cm^2 per sec) leads to a value of $t_0 \approx -15$ sec. This is to be compared to the value of -35 sec determined from Figure 2. When (8) is applied to other data obtained with this probe the theoretical value of t_0 is found to be algebraically too large by a similar amount (15 to 20 sec). The discrepancy evidently represents the time required for the temperature in the insulating tubing near the axis of the probe to approach an equilibrium gradient. The air should not seriously affect the results in view of its high diffusivity. Although this discrepancy between observed and computed values of t_0 obviates the possibility of determining accurately the volume specific heat with the present probe, by subtracting 15 sec from the t_0 value indicated by (8) it has been possible to account approximately for the empirically determined value of t_0 over a wide range. Thus for the present instrument (8) provides a useful guide to the minimum permissible duration of a test in terms of α and S, and of the time range over which it is permissible to determine t_0 by curve fitting.

Summary—The probe described in this paper can be used in the field to determine the thermal conductivity of frozen and thawed soil materials, snow, and ice. The test must be of long enough duration that the temperature increases approximately logarithmically with time throughout a substantial time interval. Within this time interval the conductivity can be determined from the slope of a graph of Θ versus $\ln(t + t_0)$, where t_0 is determined by the curve-fitting technique described. The minimum permissible duration of a test depends upon the thermal properties of the test medium as well as the thermal properties and dimensions of the probe. The necessary test duration for various media can be estimated with the aid of (7ab). For most media a 15-minute test is adequate. Certain materials with low density, such as dry peat and snow, require tests of greater duration.

If a probe were composed almost entirely of highly conducting metal, the rate of temperature rise within it should be given to a good approximation by (6). In this case the volume specific heat of the test medium could be determined with the aid of (7ab) and (8) after K and t_0 were determined by the curve-fitting technique. This would permit a simultaneous determination of the thermal conductivity and thermal diffusivity.

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A Method of Forecasting Stages on Flat Rivers

WILLIAM E. RAY AND HERMAN F. MONDSCHEIN

Abstract—In the course of daily forecasting of river stages at selected points along the Illinois and Mississippi Rivers, it has been noticed that conventional mainstem forecasting procedures proved somewhat inadequate in cases where rivers were generally flat. Such methods usually involve multiple graphical correlations of two inflow with two outflow stage values, or Muskingum routing methods. In the study reported here, an entirely new approach to the problem on the Illinois River was developed. It involved the use of a downstream stage parameter as an index of slope and channel storage, and, when used in conjunction with modifications of standard procedures for predicting discharge inflows, could more adequately reproduce the observed stage hydrograph at the upstream point. Results achieved using this new approach are demonstrated in two actual flood rises.

PURPOSE AND SCOPE OF THE STUDY

The purpose of the study is to demonstrate a new approach to the rather difficult and perplexing problem of forecasting daily river stages at various points along flat stream channels. The results of previous methods were never considered entirely satisfactory when applied to portions of the Illinois River. While these methods, when employed on other streams, have proven themselves to be more than adequate, they left much to be desired on unusually flat and sluggish river reaches. In scope and treatment the study is empirical, and is based on analyses of important rises during ten years of record from 1942 to 1952. The paper is limited to the discussion of the various relations involving the use of the downstream stage parameter for forecasting stages on the Illinois River. It does not concern itself with the auxiliary relations for other mainstem and tributary points, even though they are an integral part of the overall Illinois River forecast scheme, since they involve other principles beyond the scope of this paper. No attempt is made to deduce quantitatively the hydraulic principles involved in a relationship of this nature. Suffice it to say that what has been sought, and to a degree attained, is a practical working tool. Such a tool is expected to aid in more accurate prediction of stages on relatively flat river reaches and to minimize the subjective error.

INTRODUCTION

In order to forecast river stages in its area of responsibility, the U. S. Weather Bureau River Forecast Center in St. Louis, Missouri developed and currently uses a set of procedures and streamflow routing methods as described by *Linsley* [1951]. Experience, however, necessitated some improvement in the relations so developed on the Illinois River. This river may be described as one having a rather steep headwater area draining into a relatively flat basin, in contrast to nearby river basins such as the Des Moines, which has a slope more characteristic of the Upper Mississippi region. The outstanding features of this contrast may be seen in Figure 1. A comparison of the discharge hydrographs of the maximum floods at representative points on each river serves to illustrate the contrasting shapes resulting from these differing slopes. This may be seen in Figure 2.

The inflow-outflow balance of the lower Illinois then, is determined by a storage factor which is a great deal larger than that usually encountered in a river of such limited normal channel capacity. The result is that in a wet season the storage may increase steadily for several weeks at a time. This cumulative storage characteristic has been found to affect the stages observed throughout the reach from LaSalle to the mouth for several months. Thus, the downstream stage factor, as an index of this storage, became an important parameter when used either in conjunction with discharge or with an upstream stage.

PROCEDURE

Development of discharge relationship—First, in order to predict more accurately the discharge as measured at the U. S. Geological Survey sloperated stations along the river and published in the Water Supply Papers of that agency, use was made of a modification of the Muskingum routing method (G. T. McCarthy, 1938, unpublished manuscript, The unit hydrograph and flood routing) on the electronic streamflow routing analogue [*Linsley* and others, 1948; *Kohler*, 1952]. This is the electronic device developed by the U. S. Weather Bureau to facilitate development and operational

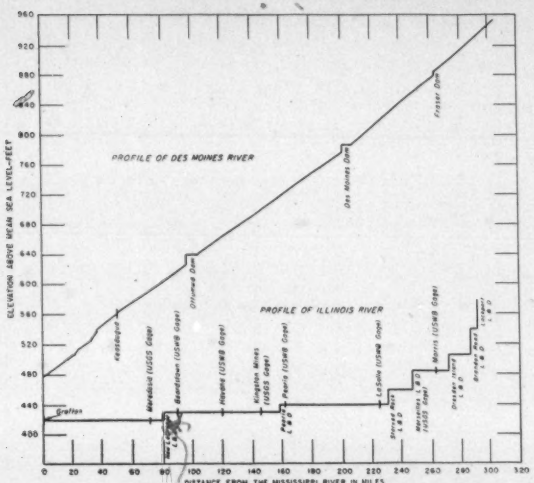

FIG. 1 — Comparative profiles, Illinois and Des Moines Rivers

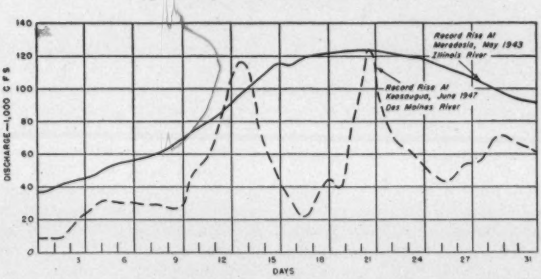
Record Rise At Meredosia, May 1943 Illinois River
Record Rise At Keosauqua, June 1947 Des Moines River
DISCHARGE—1,000 C.F.S.
DAYS

FIG. 2 — Comparative hydrographs, Illinois and Des Moines Rivers

use of river forecast procedures. This modification consisted of the routing of discharge in layers, with various time lags and routing coefficients applied to each. Such a procedure was made necessary by the failure of the original Muskingum routing method to reproduce the entire observed hydrograph adequately, despite painstaking manipulation of routing values. These difficulties were brought about by radically changing channel width at different river levels, each layer requiring individual routing treatment. Marked improvement in the computed hydrograph resulted. Throughout the development of the discharge relation, however, large channel storage was indicated, for unusually large routing coefficients were required to reproduce the hydrograph of discharges published by the U. S. Geological Survey adequately.

In the development of the discharge relationship only the flows between the two points in the particular reach in question were considered, without regard to the existence or effect of high stages downstream caused by backwater from the Mississippi or from channel storage. Since the individual discharge-routing relations, so developed for each reach on the Illinois proved capable of adequately reproducing, for river forecasting pur-

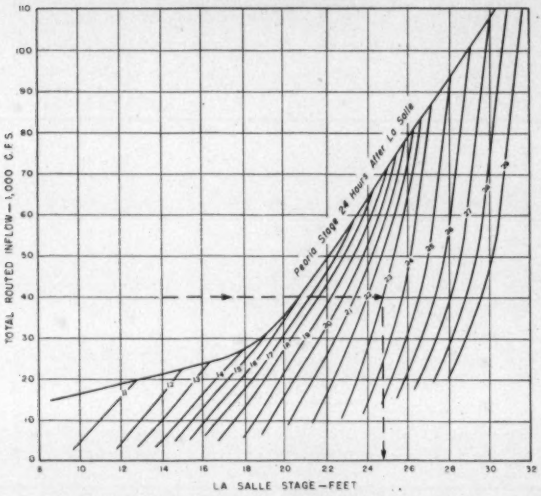

FIG. 3 — Forecast relation, LaSalle

poses, the observed U. S. Geological Survey discharge hydrograph at each outflow point, it is felt that the theoretical backwater effect on discharge routing in a given reach can be eliminated from direct treatment.

Improvement in stage relationship—The problem was not solved, however, with the successful reproduction of the observed discharge hydrograph, for the Weather Bureau is called upon to forecast stages. Thus, the next logical step was an attempt to develop synthetic rating curves for the Weather Bureau forecast points which do not coincide with the discharge stations (Fig. 1). It was almost immediately discovered at the stations in question that the discharge loop was wider than had been suspected and a simple rating was impracticable for use in converting discharge to stage. In searching for a factor that would narrow the wide loop, it was noticed that the factor customarily responsible for a change in stage, namely the change in discharge, generally assumed only secondary importance. It was discovered that the absolute value of the stage frequently depended on the observed stage downstream more than on the incoming discharge. This is usually true for backwater conditions, and is generally noticed near the junction of two streams. This indication of the importance of river slope between stations and of backwater, in this case, from channel storage within a single stream, led to the use of the downstream stage parameter as a backwater index in the development of new stage relations on the extremely flat reaches of the Illinois River.

Examples of discharge with a downstream stage parameter—An example of discharge used in conjunction with the downstream stage parameter is the forecast relation developed for LaSalle (Fig. 3). Here the inflow used is the total flow routed from Marseilles, a short distance upstream on the main stem, and from the Fox River at Dayton, and the Vermillion River at Lowell. This inflow was plotted against the observed stage at LaSalle and labeled with the stage observed one day later at Peoria, downstream. The resulting relation, a family of curves of Peoria stage, is essentially a rating curve for LaSalle with a correction parameter for the effects of backwater from channel storage as measured by the stage at Peoria. The use of the next day's downstream stage produced the best correlation, and is probably a reflection of the routing in the 63-mile reach, the backwater effect from channel storage and the ungaged local inflow in the reach. It yielded the best results on the recession of the LaSalle hydrograph with little effect on the

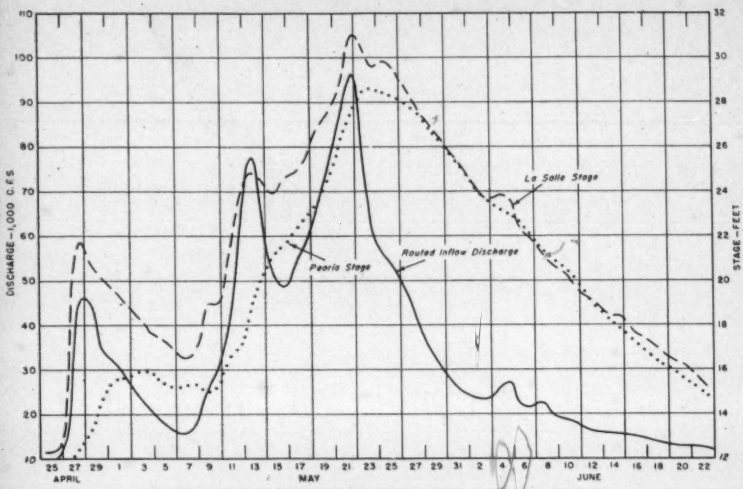

FIG. 4 — LaSalle and Peoria hydrographs, April–June 1943

rising limb. Obviously, heavy local inflow in the reach below LaSalle would have no effect on the previous day's stage at LaSalle, a difficulty which might be expected from the nature of the relation. At any rate, such a condition, which would result in a faulty computed value for the previous day's LaSalle stage, is largely academic, and in forecasting practice a new series of computations would ensue following a heavy rain.

This method of attack resulted in the only explanation found thus far, of the extremely sluggish recessions observed at LaSalle in the face of rapidly decreasing discharges as shown in Figure 4. The general streamflow pattern at this point shows the rising limb of the stage hydrograph taking the pattern of the rise in inflow discharge, while the falling limb matches the stage recession downstream at Peoria. At LaSalle is the most outstanding illustration of accumulated storage persisting beyond the period normally expected in rivers of this size. The location of the station at the point where the slope of the river undergoes a radical change (Fig. 1), is the most probable source of this rather unique type of behavior.

The Beardstown relation (Fig. 5) is another example of discharge being used with a downstream stage parameter in order to predict the stage at the upper end of the reach. The discharge at Meredosia, a few miles below Beardstown is plotted against the Beardstown stage and labeled with the stage at Grafton situated at the mouth of the Illinois. Grafton is used even though it is not a parameter independent of backwater, because it represents the slope and storage effects at the mouth of the Illinois. The backwater in this instance results from the flow of the Mississippi as well as the Illinois. At times this backwater even may result from extreme Missouri River flows which enter the Mississippi abnormally just below Grafton and behind the Alton Dam, which is located in the Mississippi just above its normal junction with the Missouri River.

Grafton is forecast by independent flow methods involving discharges at Alton downstream correlated by means of a tributary backwater correction graph employing St. Charles stages on the Missouri River. Alton discharges are forecast by combining separate flow routings of the Mississippi and Illinois Rivers. The methods on the Mississippi then, closely parallel those on the Illinois, involving discharge routing to the mouth of the Missouri, followed by successive backwater stage computations upstream. A more detailed description of the method of forecasting Grafton is beyond the scope of this paper, which is concerned with the applica-

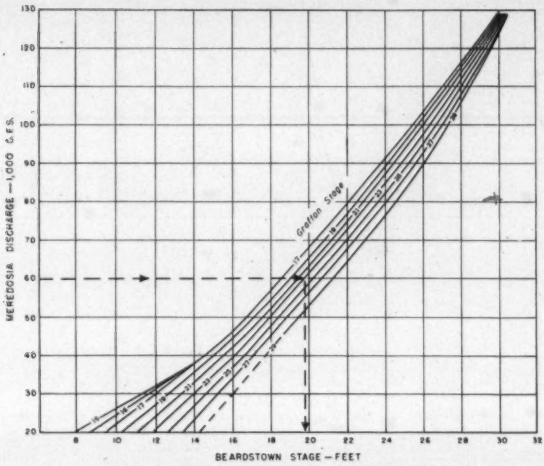

FIG. 5 — Forecast relation, Beardstown

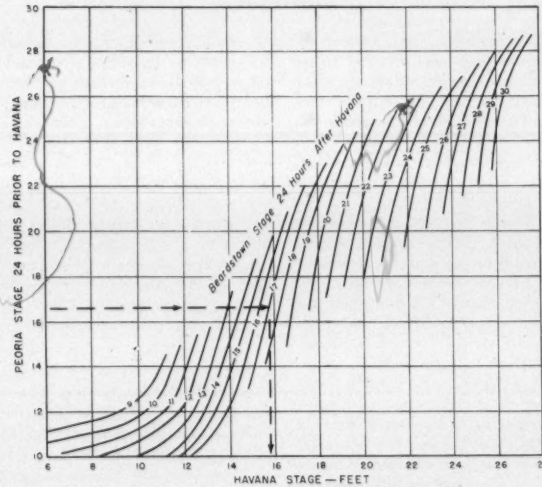

FIG. 6 — Forecast relation, Havana

tion of the downstream stage parameter to the lower Illinois River.

Since the Beardstown relation with Grafton as a parameter more nearly approaches the usual concept of backwater, namely from another stream, rather than from channel storage, the effect is felt more uniformly throughout the range of stages at Beardstown. This is in contrast to the increasingly

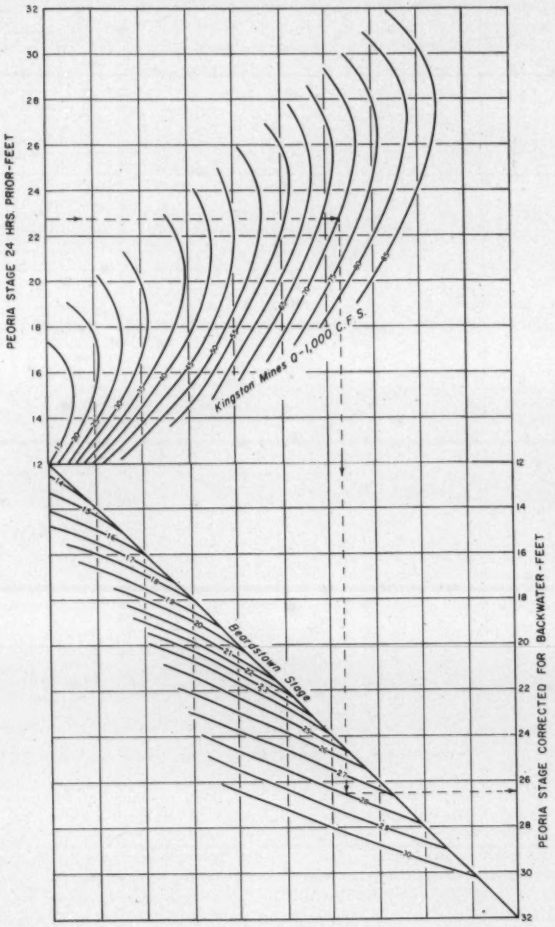

FIG. 7 — Forecast relation, Peoria

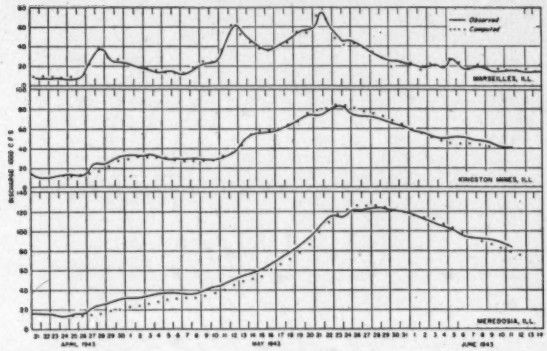

FIG. 8 — Test results, discharge hydrographs, Illinois River flood of April–June 1943

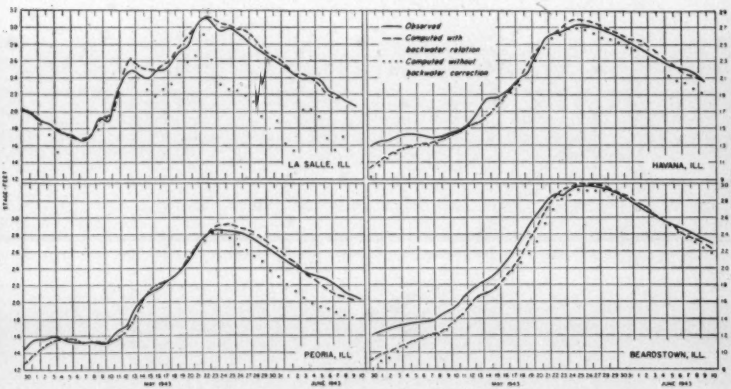

FIG. 9 — Test results, stage hydrographs, Illinois River flood of April–June 1943

greater effect of high downstream stages as observed in the LaSalle relation. In both cases the relation is essentially a rating curve with an additional parameter involving backwater.

Use of downstream and upstream stages to predict an intermediate stage—The forecast relation developed for Havana (Fig. 6) is an example of downstream and upstream stages being used as a slope factor to determine the resulting stage at the intermediate station. The previous day's stage at Peoria upstream was plotted against the observed stage at Havana and labeled with the following day's stage at Beardstown downstream, resulting in a family of curves of Beardstown stage. At Havana, as at LaSalle, difficulty was encountered explaining both the shape and magnitude of the stage hydrograph, when only the stage at the upper end of the reach was used to make the forecast at the downstream point. Use of Beardstown stage as an index of the slope, made it possible to more closely approximate the observed stage magnitude at Havana.

The forecast relation for Peoria—The forecast relation for Peoria (Fig. 7) required two quadrants, unlike the others which involve only one. The upper quadrant, in reality a 24-hour change in

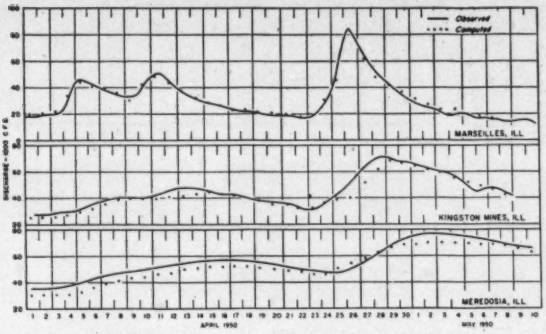

FIG. 10 — Test results, discharge hydrographs, Illinois River flood of April–May 1950

stage relation, was developed by plotting one Peoria stage against another, the two separated by a 24-hour interval. The resulting points were labeled with the flow at Kingston Mines a short distance downstream, which was simultaneous with the more recent of the two Peoria stages. This latter stage is then corrected for any possible backwater effect by the lower quadrant, the modification consisting of a family of curves of Beardstown stage downstream. Since the variables of this two quadrant graph are intercorrelated each portion must be used in conjunction with the other. From these graphs it may be seen that the first step of the Peoria forecast consists of the independently made discharge forecast, where the backwater effect on discharge is reflected in the large storage coefficient necessary to reproduce the discharge hydrograph. The second step is the preliminary conversion to stage by means of a 24-hour change in stage relation. Finally, in the last step, determination of the effect of backwater from channel storage on the Peoria stage is achieved through use of a conventional backwater graph. The parameter, Beardstown stage, is not the usual independent variable, however, but one which represents the flow that has passed Peoria, yet still affects the Peoria stage long after the water has passed downstream.

Results—In the following examples which are intended to portray the results achieved using the methods described, namely, the conversion of flow to stage where flat slopes are involved, two highly dissimilar flood periods were purposely selected. One case, that of 1943 (Fig. 8 and 9), was the record flood and was characterized by large tributary inflow in the lower reaches of the Illinois River. The 1950 flood (Fig. 10 and 11), on the other hand, was predominantly from upstream sources. The tests were made to determine the accuracy of the forecasting method when applied through the entire reach of the Illinois River below Morris without check-in at intermediate main river points. Observed flows were used at tributary gages as recorded in the U. S. Geological Survey Water Supply Papers. Observed stages on the main stem of the Illinois were used at Morris, near the first inflow point upstream, and at Grafton on the Mississippi at the junction of the Illinois. Grafton represents the first backwater parameter downstream. The use of observed rather than computed stages at Grafton appears justified for purposes of this test since it is forecast by methods beyond the scope of this paper, and described in general terms above. Use of computed Grafton, further, would necessitate a complete description of its forecast procedure, a factor which would unnecessarily complicate and widen the scope of the paper. In any event the Grafton relationship would have to be considerably in error to affect the results on the Illinois River greatly. This can be seen from examination of Figure 5. The flow at Marseilles, above the flat reach of the Illinois under discussion, was obtained by conversion of the observed Morris stages by means of a simple synthetic rating curve. These flows were routed downstream and combined with the observed tributary flows using the storage routing method developed for the Marseilles-Kingston Mines reach mentioned previously. Runoff volumes in the intervening ungaged area were fixed, wherever possible, by the

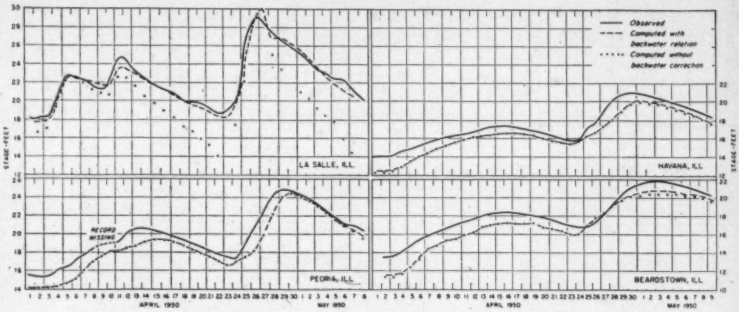

FIG. 11 — Test results, stage hydrographs, Illinois River flood of April–May 1950

use of observed storm runoff volumes derived from daily discharges published in the U. S. Geological Survey Water Supply Papers for small sub-basins within the large ungaged area. In this manner, the computed flow hydrograph for Kingston Mines was developed.

Proceeding downstream in flow the computed Kingston Mines hydrograph was routed to Meredosia with the observed tributary and runoff flows for the intervening area added on, using the storage routing method developed for the Kingston Mines-Meredosia reach. Having arrived at Meredosia with computed flows, the computed Beardstown hydrograph was developed using observed Grafton stage, the downstream backwater parameter in this reach. Once the computed hydrograph for Beardstown, the farthest downstream forecast point on the Illinois River, was attained, successive computed stage hydrographs were developed progressively upstream. In each case only the computed stage values were used as the downstream parameter to convert computed flows to stage at each point.

The rising limb of the observed stage hydrographs at each point exceeds the computed by a fairly constant amount. This difficulty results from insufficient volume, which can be attributed to the fact that the base flow in the fairly large ungaged local area was not considered. The effect is negligible for short reaches, but is cumulative and becomes noticeable when routing through a chain of these reaches. The resultant error is of minor consequence in forecasting, because a base flow adjustment can be readily made from current data.

CONCLUSION

From the test hydrographs it may be seen that the greatest backwater correction on the flat lower reach of the Illinois is made at the upstream point. In addition, in the record 1943 case, which involved major local inflow from downstream tributaries, the backwater correction appears to increase progressively upstream, with the greatest effect at LaSalle, the farthest forecast point from the junction of the Mississippi in the flat reach of the Illinois. This occurs despite the existence of the record flood at Grafton situated at the junction of the two streams. This suggests that backwater from the Mississippi is less important in the face of channel storage backwater exerted by the Illinois upon itself. In fact the latter may be so great, that the downstream stage, as an index of channel storage backwater, must be considered as a separate parameter, in the endeavor to convert flow to stage. This is especially important on recessions, where the inflow into a reach decreases at a much more rapid rate than does the outflow, due to the great accumulation of channel storage and the backwater resulting from it. The downstream stage parameter represents an empirical approach to the problem and provides an efficient aid to the forecasting of river stages on the Illinois River.

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Relationship of Unmeasured Sediment Discharge to Mean Velocity

B. R. COLBY

Abstract—Unmeasured sediment discharges were computed by subtracting the measured suspended-sediment discharges at alluvial sections from total sediment discharges that had been either measured at nearby contracted sections or computed from the modified Einstein procedure. Average curves show a general increase of unmeasured sediment discharge per foot of stream width as a function of about the third power of the mean velocity. At constant mean velocity the unmeasured sediment discharge per foot of width generally increases with concentration, especially with suspended sands concentration adjusted for depth of stream. Such adjusted concentrations of suspended sands seems to be reasonably good measures of the availability of sands. This availability is the relative rate of transport of sands for a given condition of flow and is related to particle sizes and cohesiveness of sediments of the stream bed and banks. Relationships of unmeasured sediment discharge to mean velocity and to concentration can be applied successfully in several kinds of sediment computations.

Introduction—The rate of suspended-sediment discharge of a stream is usually based on an average of the concentrations of depth-integrated samples of suspended sediment for each of several verticals in a cross section. This average concentration is multiplied by the rate of water discharge and by a conversion factor to obtain the suspended-sediment discharge in tons per day or in other suitable units. Thus, the measured suspended-sediment discharge is computed from all the flow through the cross section but from less than the true average suspended-sediment concentration, because depth-integrating samplers do not normally collect water-sediment mixture within three to five inches of the stream bed, and suspended-sediment concentrations are highest near the bed. The difference between the total sediment discharge of a stream and the measured sediment discharge may be termed the unmeasured sediment discharge. The unmeasured sediment discharge consists of bed-load discharge (the discharge of sediment that moves along in essentially continuous contact with the bed of the stream) and part of the suspended sediment that is discharged below the lowest point of travel of the sampler nozzle in the vertical. The ratio of the sediment discharge through the sampled zone to the total sediment discharge has been discussed by *Chien* [1952].

This paper points out relationships to mean velocity of different factors that determine the unmeasured sediment discharge and gives empirical relationships for computing unmeasured sediment discharge from mean velocity and concentration of suspended sediment. In general, the theoretical relationships and many of the assumptions that were stated by *Einstein* [1950] are followed in the paper.

Unmeasured sediment discharge—For simplicity, the unmeasured sediment discharge and its theoretical relationship to mean velocity are discussed, as much as possible, in terms of water and sediment discharge per unit of stream width and for one range of particle sizes.

The unmeasured sediment discharge per unit width can be expressed by

$$q_{us} = i_B q_B - k c_m q_{uw} + k \int_{2D}^{a} c_y \bar{u}_y \, dy \qquad (1)$$

in which q_{us} is the unmeasured sediment discharge of particles in the size range for which the geometric mean size is D

i_B is the fraction of bed load in the size range
q_B is the rate of bed-load discharge per unit time and unit width
k is a conversion constant
c_m is the concentration from depth-integrated samples of sediment of the given size range
q_{uw} is the water discharge through the unsampled zone
a is the distance from the stream bed to the lowest position of the sampler nozzle in the vertical during sampling
c_y is the suspended-sediment concentration of particles of the size range at a point in the vertical
$\bar{u}_y$ is the time-averaged velocity at the point
y is the distance of the point above the stream bed

The two positive terms on the right-hand side of (1) are for bed-load discharge and for total discharge of suspended sediment through the unsampled

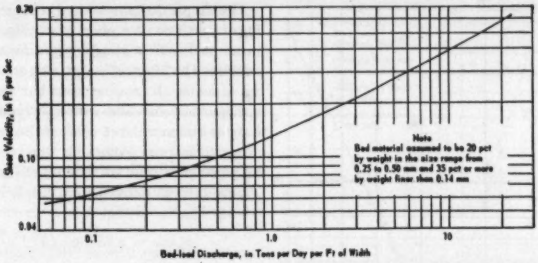
0.30
0.10
0.04
Shear Velocity, in Ft per Sec
0.1
1.0
10
Bed-load Discharge, in Tons per Day per Ft of Width
Note
Bed material assumed to be 20 pct by weight in the size range from 0.25 to 0.50 mm and 35 pct or more by weight finer than 0.14 mm

FIG. 1 – Relationship of shear velocity to rate of bed-load discharge of particles from 0.25 to 0.50 mm

zone. The negative term represents that part of the suspended-sediment discharge that occurs through the unsampled zone but is computed in the measured suspended-sediment discharge. Sediment particles finer than sands (< 0.062 mm) are nearly uniformly distributed throughout the vertical, and the unmeasured increment of these fine sediments is usually negligible. Hence, (1) will be discussed for a range of particle sizes within the limits of sand sizes, a size range for which unmeasured sediment discharge is significant.

Theoretical relationships to mean velocity—The different parts of the right-hand side of (1) are shown in the following discussion to be functions of mean velocity, but they vary somewhat with other factors.

According to *Einstein* [1950], the rate of bed-load discharge, $i_B q_B$, depends principally on the product of the surface slope of the stream and the hydraulic radius with respect to the sediment particle but varies with other parameters. *Colby* and *Hembree* [1955, pp. 83–89] simplified the computation and made the bed-load discharge per unit width and for a given geometric mean size of particles having a specific gravity of 2.65, expressible as one of two possible functions of the shear velocity. The physical significance of this computed bed-load discharge is somewhat uncertain. The function to be used depends on whether the geometric mean particle size is larger or smaller than 2.5 times the particle size for which 35 pct of the bed material by weight is finer. The curve for bed-load discharge per foot of width as a function of shear velocity is shown on Figure 1 for sediment in the size range from 0.25 to 0.50 mm (geometric mean size is 0.35 mm) and for bed material of which 20 pct by weight is in this size range. The curve is approximately applicable only if D_{35} is equal to or less than 0.14 mm. The other of the two functions is used if D_{35} exceeds 0.14 mm. The bed-load discharge changes rapidly with changes in the shear velocity.

The shear velocity u_* for the curve of Figure 1 was computed from the measured mean velocity $\bar{u}$ in the cross section and from a velocity equation [*Keulegan*, 1938, pp. 707–741] in the form

$$\bar{u}/u_* = 5.75 \log_{10} (12.27\, d/\Delta) \qquad (2)$$

in which d is the depth and Δ is the apparent roughness. The ratio of mean velocity to shear velocity varies directly with the logarithm of the ratio of 12.27 times the depth to the apparent roughness and hence changes slowly with changes in the latter ratio. That is, the mean velocity is roughly proportional to the shear velocity. (The number 12.27 is for the cross section of a natural stream. Integration of (3), below, throughout the depth of a stream gives about 11.1.) Although some assumptions and approximations are involved in the relationship of Figure 1, the large effect of shear velocity and hence of mean velocity on the rate of discharge of sediment as bed load is evident.

Discharge of suspended sands of a given size range through the unsampled zone $kc_m q_w$ (from depth-integrated measurements) varies with mean velocity. Figure 2 shows a rough correlation of measured concentration of suspended sands with mean velocity for the gaging-station section of the Niobrara River near Cody, Nebr. In general, the concentration of measured suspended sands increases at this section with about the 2.1 power of the mean velocity. This type of relationship can be expected to hold reasonably well for a particular cross section of an alluvial stream. The slope of the relationship curve may be much the same from one stream to another. However, the concentration

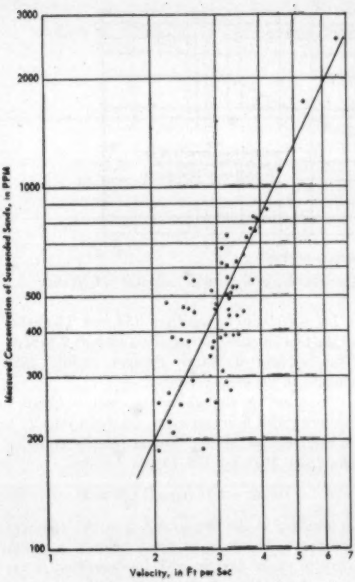

FIG. 2 – Relationship between concentration of suspended sand and mean velocity, Niobrara River near Cody, Nebr.

of suspended sands at a given velocity is likely to differ appreciably from one stream to another because size distributions and quantities of sands that are available for transport differ widely.

The other variable that determines the measured discharge of suspended sediment through the unsampled zone is the flow q_{us} through that zone. This flow per unit width of channel is the product of the average velocity through the unsampled zone and the height $(a - 2D)$ of the zone. The height of the zone is relatively constant, and the theoretical average velocity in the unsampled zone is obtained by integrating an equation for velocities at a point such as (3), the same equation that would be integrated to compute mean velocity for the entire vertical. Therefore the average velocity through the unsampled zone should be about proportional to the mean velocity for the entire vertical except for the effect of changes in the ratio of depth of the water to depth of the unsampled zone.

The suspended-sediment discharge, $k \int_{2D}^{a} c_y \bar{u}_y \, dy$, of particles of a given size range through the unsampled zone is also largely a function of mean velocity. The limits of integration are usually much the same for all cross sections but vary somewhat with particle size and with the type of sediment sampler and method of using it. Both velocity and concentration at points in the vertical within the unsampled zone are functions of mean velocity.

Equ. (2) was derived from (3), below, for time-averaged point velocity $\bar{u}_y$

$$\bar{u}_y/u_* = 5.75 \log_{10} (30.2\, y/\Delta) \qquad (3)$$

or

$$\bar{u}_y = 5.75\, u_* (\log_{10} 12.27 + \log_{10} d - \log_{10} \Delta + \log_{10} 30.2 + \log_{10} y - \log_{10} 12.27 - \log_{10} d)$$

which combines with (2) to give

$$\bar{u}_y = \bar{u} + 5.75\, u_* \log_{10} (2.46\, y/d) \qquad (4)$$

According to this equation, the velocity at a point is equal to the mean velocity in the vertical plus or minus a quantity that varies with shear velocity and with relative distance of the point above the stream bed.

The concentration c_y at a point in the vertical in the unsampled zone depends jointly on the measured concentration c_m and on the vertical distribution of concentration and is, therefore, closely, but complexly, related to mean velocity. The measured concentration of suspended sands has already been shown (Fig. 2) to be related to mean velocity. The vertical distribution of concentration for particles of a given size range has an exponential measure z which can be computed by trial and error from the rate of bed-load discharge and from the product of measured concentration for the size range, depth of the sampled zone, and mean velocity in the sampled zone. An alternative computation bases z on the fall velocity of the sediment particles and on the shear velocity. Whichever method of computation is used, the vertical distribution of sediment concentration is a function of mean velocity but also varies with water temperature, stream depth, and channel roughness.

The different terms in the right-hand side of (1) are thus individually related to the mean velocity, but the relationships are complicated even for one range of particle sizes. Hence, a theoretical method of computing unmeasured sediment discharge from relationships to mean velocity and to other factors becomes difficult and usually requires extensive

field data. Simpler relationships, which, although only approximate, may be satisfactorily accurate for many uses, can be defined empirically.

Empirical relationships—About 180 experimental determinations of unmeasured sediment discharge at a normal section were readily available. Each determination was the difference between measured sediment discharge at a total-load section and at a normal section. By 'total-load section' is meant a contracted section at which practically the total sediment discharge of the stream is in suspension and can be sampled satisfactorily with a depth-integrating sampler. By 'normal section' is meant a section at which nearly all the stream bed and sometimes the banks, too, are of readily shifting alluvium. Unmeasured sediment discharges divided by the width of the normal section are plotted on Figure 3 against mean velocity at the normal section. Individual points scatter widely from the curve, but the unmeasured sediment discharge increases on the average with about the third power of the mean velocity. The equation for computing the unmeasured sediment discharge Q_{um} of all particle sizes in tons per day from the average curve is

$$Q_{um} = 0.28\ (\bar{u})^{3.1}\ w \qquad (5)$$

in which $\bar{u}$ is the mean velocity in the cross section in feet per second, and w is the width in feet. Within the limits of its experimental definition, this equation is roughly applicable to the computation of unmeasured sediment discharge at a cross section.

As implied in the preceding paragraph, the curve of Figure 3 is intended to show the average unmeasured sediment discharge for given mean velocities. Therefore, it was drawn through arithmetic averages of the unmeasured sediment discharges for each of several ranges of mean velocity. The other curves in this paper were likewise drawn through arithmetic averages of the dependent variable. The curve of Figure 3 is entirely unsuited for the estimating of mean velocity from unmeasured sediment discharges. It differs considerably from a least-squares curve as ordinarily drawn because the slope of such a curve would depend not only on the average unmeasured sediment discharges for given ranges of mean velocity but also on the total range of velocities that are covered by Figure 3.

The plotting of points on Figure 3, especially points for Fivemile Creek, seems to indicate that the unmeasured sediment discharge may be higher

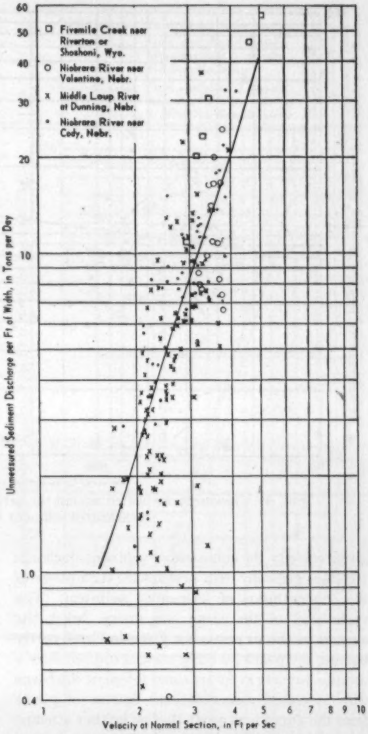

FIG. 3 – Relationship between unmeasured sediment discharge and mean velocity

for a given velocity if the suspended-sediment concentration is high. Hence, ratios, called ratios of departure, were computed for the points on Figure 3. Each ratio was the quotient that was obtained by dividing an experimental determination of unmeasured sediment discharge per foot of width by the unmeasured sediment discharge per foot of width as indicated by the mean velocity and the curve of Figure 3. The ratios were then plotted (Fig. 4) against the mean concentrations of depth-integrated samples at the normal sections to see whether some of the scatter of individual points was associated with differences in concentration of suspended sediment. The slope of the curve of Figure 4 is poorly defined. It indicates that for a

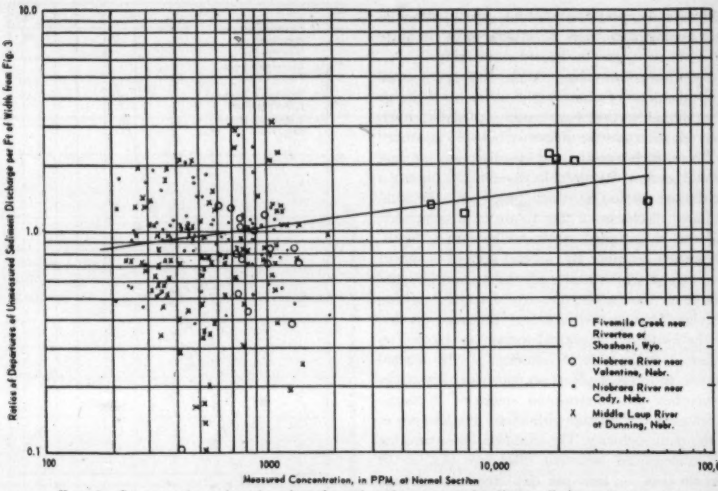

FIG. 4 – Concentrations plotted against the ratios of unmeasured sediment discharge to average unmeasured sediment discharge from Figure 3

given velocity the unmeasured sediment discharge increases generally with perhaps the 0.35 power of the concentration of suspended sediment. (The upper end of the curve was drawn below the average of the six points for Fivemile Creek partly because the points for other stations did not show a definite increase in unmeasured sediment discharge with increased concentration.) Scatter of points from the curve is so great that no further attempt was made to explain the scatter in terms of other factors.

The curve of Figure 3, and hence (5), should be understood to express average variation of unmeasured sediment discharge with mean velocity. The curve probably would be considerably different if other factors were kept constant and only velocity and unmeasured sediment discharge were permitted to vary. Actually, an increase in velocity is usually accompanied by an increase of suspended-sediment concentration. Such an increase will certainly occur if the supply of sediment remains constant in terms of both quantity and particle sizes. The supply of sands may be approximately constant at a cross section of an alluvial stream but is likely to differ widely from stream to stream or from one part of a stream to another. Therefore, the adjustment of Figure 4 may not be needed to compute unmeasured sediment discharges for different velocities and concentrations at a particular cross section because the curve of Figure 3 already contains an adjustment for average change in concentration with change in velocity.

If the scatter from the curves of Figures 3 and 4 was caused entirely by inadequacy of the correlations, these curves would be unsatisfactory for computing unmeasured sediment discharge. However, much of the scatter results from inaccuracy of the determinations of unmeasured sediment discharge. These determinations, although very valuable information, are differences between two measured sediment discharges each of which is likely to be somewhat inaccurate. Furthermore, the normal sections were from a few hundred feet to more than a mile from the total-load sections, and changes, either temporary or semipermanent, in net rate of scour or fill between the sections may cause large inaccuracies in the determinations. Some method for experimentally determining more exact unmeasured sediment discharges is badly needed to make the experimental information more suitable for establishing empirical relationships to parameters other than mean velocity.

Computed unmeasured sediment discharges as

functions of mean velocity—Unmeasured sediment discharges can be computed from information at a single cross section. Although the computation procedure is complicated and uncertain in some details, the unmeasured sediment discharges thus computed have a more consistent relationship to mean velocity than experimental determinations have. One procedure for computing total sediment discharge by extrapolating and interpreting data for a single section has been explained by *Colby* and *Hembree* [1955, pp. 66–98]. It is known as the modified Einstein procedure and requires mean velocity, width, and average depth of the cross section, average depth at sampling verticals, water temperature, bed-material samples for particle-size analysis, and depth-integrated samples of suspended sediment to be analyzed for particle size and concentration. Some results of applications of the procedure have been discussed by *Schroeder* and *Hembree* [1956].

Many unmeasured sediment discharges were computed by subtracting measured sediment discharges at a normal section from total sediment discharges as computed for the same times by the modified Einstein procedure. These unmeasured sediment discharges per foot of width were plotted against mean velocity. One average curve was drawn for sediment stations in the Rio Grande basin and another for other stations. The two curves are shown on Figure 5 together with the average curve from Figure 3. The three curves are reasonably consistent and would agree better if adjusted for differences in average concentration.

Adjustments for concentration—Readily available unmeasured sediment discharges per foot of width from modified Einstein computations were listed without screening to eliminate those that were computed from unsuitable field data. Then each one was divided by the unmeasured sediment discharge per foot of width as indicated by the mean velocity and by the appropriate curve of Figure 5. The quotients were plotted against concentration of suspended sediment to define curves *B* and *C* of Figure 6. Curve *A* of Figure 6 is redrawn from Figure 4 for comparison. For a given mean velocity, these curves indicate an increase in unmeasured sediment discharge with increasing concentration of suspended sediment. Such an increase is logical for sediment coarse enough to be appreciably more concentrated near the stream bed than higher in the vertical. However, the concentration of finer sediment probably has little relationship to the quantity of unmeasured sediment discharge.

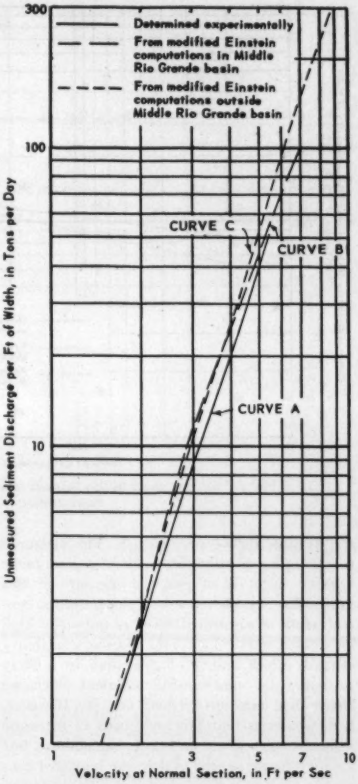

FIG. 5 – Comparison of average curves of unmeasured sediment discharge plotted against mean velocity

An average adjustment for concentration (Fig. 6) is insufficient to explain the low unmeasured sediment discharges that were computed by the modified Einstein procedure for some sediment stations. Perhaps the effective supply of sands that can be picked up readily, which depends on configuration of the stream bed as well as on sizes and quantities of sediment, is much lower relative to the flow at these stations. If so, a measure of the availability of sands might correlate well with departures of unmeasured sediment discharge from

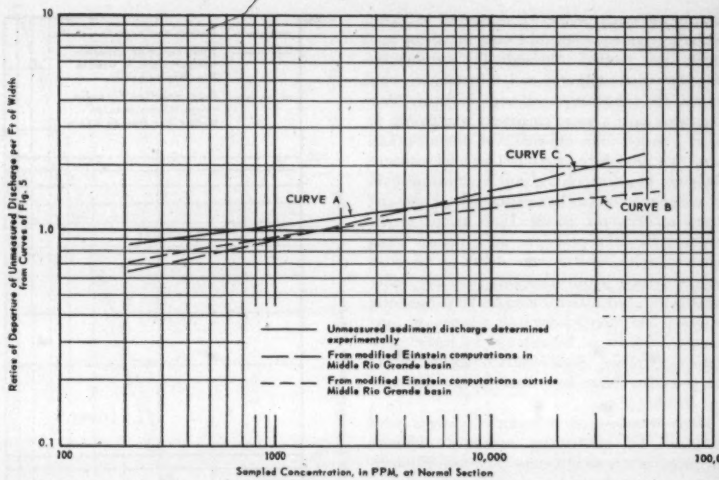

FIG. 6 – Average relationships between ratios of departure from the curves of Figure 5 and concentration of suspended sediment

the average curves of Figure 5. The measured concentration of suspended sands at a given mean velocity might be a practical measure of this availability. In other words, if the measured concentration of suspended sands is unusually high for a given mean velocity, the effective availability of sands is high, and this high availability is likely to make the unmeasured sediment discharge higher than usual for the given velocity. However, in two streams that flow over beds of the same sediment composition and same configuration but widely different depths of flow, the measured concentration of suspended sands for equal velocities will be considerably lower for the deeper stream. Thus, measured concentrations of suspended sands require adjustment for depth of flow to make them reasonably consistent measures of the effective availability of sands, and the relative adjustment for depth will vary with mean velocity.

Figure 7 shows relative concentrations of suspended sands for different depths and velocities. It is based on 100 ppm of suspended sands (any convenient concentration might be used) at a mean velocity of one foot per second and a depth of two feet. The concentration for a constant depth of two feet was assumed to increase with the square of the velocity. Adjustments for depth at different velocities were computed from theoretical relationships and for an assumed effective size of bed material. A better adjustment diagram than that of Figure 7 could be prepared from more numerous and precise computations and from experiments. Fortunately, an exact diagram is not necessary.

A ratio of the known concentration of measured suspended sands to the relative concentration from Figure 7 is a measure of the effective availability of sands. Availability ratios are plotted on Figure 8 against ratios of unmeasured sediment discharge to the average unmeasured sediment discharge from curve *C* of Figure 5. The curve through the plotted ratios can be used to adjust unmeasured sediment discharge for changes in availability of sands.

The points on Figure 8 represent a wide range of cross sections and concentrations. Average depths ranged from 0.4 to 55 ft, mean velocities from 1.1 to 8.0 ft per sec, widths from 15 to 2760 ft, measured suspended-sediment concentrations from 57 to 140,000 ppm, concentrations of suspended sands from 5 to 26,600 ppm, and computed unmeasured sediment discharge per foot of width from 0.4 to 346 tons per day. In view of these wide ranges and the inaccuracies in computed unmeasured sediment discharges, scatter of points from

the average curve of Figure 8 is not excessive. Of 162 plotted points, 142 are within 50 pct, and 113 are within 25 pct of the average curve. Some points farthest from the curve, for example the low points at availability ratios of 1.05 and 2.0, are based on field data that are unsuitable for computing total sediment discharge. Points for the Mississippi River at St. Louis, Mo., scatter more than for most sediment stations because the unmeasured sediment discharge is only one to ten per cent of the total sediment discharge. Expressed in percentage of total sediment discharge, the computed unmeasured sediment discharges by the modified Einstein procedure are more accurate than for most stations, but they are less accurate than for most stations when expressed in tons per day. Also, at St. Louis the sediment load of the Missouri River is not completely mixed with the sediment load of the Mississippi River. Thus, some scatter from the average curve is caused by inaccuracies in basic data and in the computations of unmeasured sediment discharge per foot of width. Some scatter results from the inadequacy of the average relationships to give the same unmeasured sediment discharges as the much more complex modified Einstein procedure, which is theoretically more correct.

Curve *C* of figure 5, the curves of Figure 7, and the average curve of Figure 8 provide a short graphical method for computing about the same unmeasured sediment discharge that might be computed by the modified Einstein procedure. Mean velocity, width, average depth, and concentration of suspended sands are all required. The size distribution of the bed material is not needed because the availability ratio depends partly on this size distribution. An unmeasured sediment discharge, which includes all particle sizes, can be computed from these curves by dividing the measured concentration of suspended sands by the relative concentration from Figure 7 for the given depth and mean velocity. This availability ratio determines on Figure 8 a ratio of departure from Curve *C* of Figure 5. Curve *C* and the mean velocity together give an unmeasured sediment discharge per foot of width, which can then be multiplied by the ratio of departure and by the width of the stream in feet to obtain the unmeasured sediment discharge in tons per day for the cross section. Because this procedure contains an adjustment for the effective availability of sands, it may be more applicable than the modified Einstein procedure for streams whose beds have large areas of relatively unshifting material.

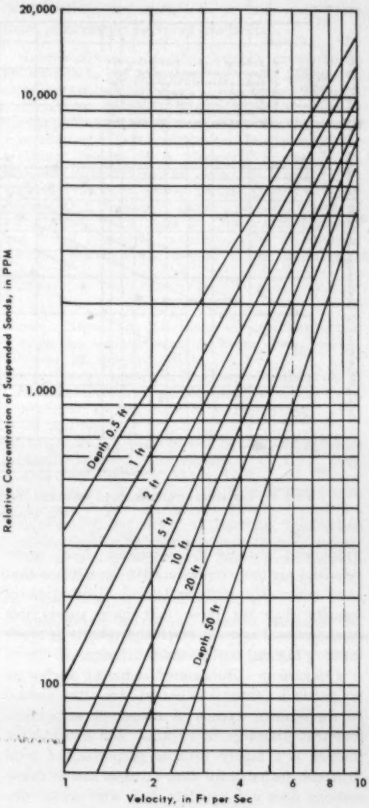

FIG. 7 – Relative concentrations of suspended sands for different depths and mean velocities

The procedure has two disadvantages. One is that it gives no breakdown of the unmeasured sediment discharge into size ranges. The other is that it requires good determinations of mean velocity because the relative concentration (Fig. 7) varies roughly as the square of the mean velocity and unmeasured sediment discharge varies as about the cube of the mean velocity. The mean velocity should be for a cross section that is normal to the direction of flow, so any horizontal angle corrections should be applied to the increments of

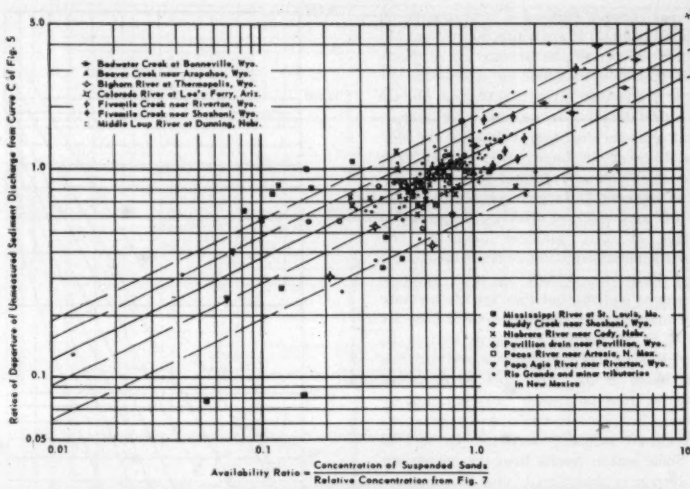
Ratios of Departure of Unmeasured Sediment Discharge from Curve C of Fig. 5
5.0
1.0
0.1
0.05
0.01
0.1
1.0
10
Availability Ratio = Concentration of Suspended Sands / Relative Concentration from Fig. 7
+50 pct
+25 pct
-25 pct
-50 pct
Bedwater Creek at Bonneville, Wyo.
Beaver Creek near Arapahoe, Wyo.
Bighorn River at Thermopolis, Wyo.
Colorado River at Lee's Ferry, Ariz.
Fivemile Creek near Riverton, Wyo.
Fivemile Creek near Shoshoni, Wyo.
Middle Loup River at Dunning, Nebr.
Mississippi River at St. Louis, Mo.
Muddy Creek near Shoshoni, Wyo.
Niobrara River near Cody, Nebr.
Pavillion drain near Pavillion, Wyo.
Pecos River near Artesia, N. Mex.
Popo Agie River near Riverton, Wyo.
Rio Grande and minor tributaries in New Mexico

FIG. 8 – Variation of unmeasured sediment discharge adjusted for mean velocity with a measure of the availability of sands

width and not to the velocities. Also, mean velocities are more representative for sections that have reasonably uniform lateral distribution of velocity than for those that have appreciable cross sectional areas in which the velocity is much lower or higher than the mean velocity.

Applications—Unmeasured sediment discharges for particular times and periods are often needed to supplement records of measured suspended-sediment discharge of streams. The unmeasured fraction is a highly variable proportion of total sediment discharge for most streams and at many stations does not correlate well with water discharge. The relationship to mean velocity does, however, provide a satisfactory basis for estimating unmeasured sediment discharges for many cross sections.

Curves of unmeasured sediment discharge per foot of width versus mean velocity can be drawn for individual sediment stations as well as for groups of stations. Because the general form of the relationship is known, perhaps six to ten determinations of unmeasured sediment discharge may define a reasonably satisfactory curve for a single station. The curve can then be used to estimate the unmeasured sediment discharge at other mean velocities for which the basic field information has not been obtained or is difficult or even impractical to obtain. Thus, the use of the curve may greatly reduce the cost of determinations of unmeasured sediment discharge. However, satisfactory extrapolation of the curve may be impossible, or at least questionable, above bankful stage or for flows when the stream is scoured to relatively unshifting bed material. The curve for an individual station can be used to estimate unmeasured sediment discharges for periods of days, months, or years if stream flow measurements are available from which to estimate mean velocities throughout the periods.

Even though no determinations of unmeasured sediment discharge have been made or no bed-material samples are available for an alluvial cross section, reasonably good estimates of the unmeasured sediment discharges can usually be made from such curves as those of Figure 5. If the concentrations of suspended sediment are either especially high or low, adjustments as indicated by the curves of Figure 6 may be applied. If sufficient information is available, Curve *C* of Figure 5 and the curves of Figures 7 and 8 can be used to give more dependable unmeasured sediment discharges, especially for concentrations and depths that differ widely from most of those that were used to define

the curves of Figures 5 and 6. This last type of computation is particularly preferable for cross sections whose stream beds are partly or mainly composed of relatively unshifting material.

Estimates of unmeasured sediment discharge from any of the curves may be used to show that for some sections the unmeasured sediment discharge is a negligible percentage of the total sediment discharge and can safely be disregarded unless the amount of the coarser sediment that is discharged is particularly significant. At the other extreme, the estimates may indicate that the unmeasured sediment discharge is, either in general or at certain seasons or rates of flow, so large a fraction of the total sediment discharge that more exact computations are justified even though such computations may require much expensive field and office work.

Unmeasured sediment discharges based principally on the relationship to mean velocity are only approximations, but the fact should be remembered that the term 'unmeasured sediment discharges' is used because no practical way is known for measuring such discharges directly and with reasonable accuracy on most streams. All that is claimed for the generalized relationships of this paper is that they usually seem to give reasonably good approximations of the unmeasured sediment discharges that might be obtained by spending hundreds or thousands of dollars on additional field measurements and office computations. These relationships are suggested to supplement but not to supersede such measurements and computations and should be revised when more exact information becomes available.

Acknowledgments—Modified Einstein computations for stations in the Missouri River basin and all the experimental determinations of unmeasured sediment discharge by differences between measured sediment discharges were made by personnel under the general supervision of P. C. Benedict, regional engineer, Quality of Water Branch, U. S. Geological Survey. D. Q. Matejka, hydraulic engineer, under the general supervision of J. M. Stow, district chemist, Quality of Water Branch, U. S. Geological Survey, prepared Curves B and did most of the work for Curves C of Figures 5 and 6 and made the computations by the modified Einstein procedure for stations in the Rio Grande basin.

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Global Distribution of the Annual Range in Soil Temperature

JEN-HU CHANG

Abstract—Maps of annual range in soil temperature at 10, 30, and 120 cm depths were constructed, using the data of 780 stations throughout the world. Temperature-range profile charts for 18 stations are presented and briefly discussed. The depth of invariable temperature is about ten meters in the tropics, and 15–20 m in middle and high latitudes.

Introduction—The annual temperature range is the difference of average temperatures between the coldest and warmest months. The distributional pattern of the annual range in air temperature is well known. A similar study for soil temperature is yet lacking. Apart from its interest to students of Earth sciences, a knowledge of the annual range in soil temperature is of practical concern to ecologists, civil engineers, architects, and others.

This study makes a preliminary attempt at mapping the distributional patterns of the annual range in soil temperature, using the data of 780 stations collected by the writer. The depths mapped were 10, 30, and 120 cm for which a relatively large number of records is available (Fig. 1, 2, and 3). In drawing the isolines in areas where there are few stations, the maps of annual air temperature range were consulted. Soil-temperature-range profile charts for 18 selected stations are plotted in Figures 4 and 5; also on each of these charts, indicated by a circle, is the annual range of air temperature.

Discussion of the maps and charts—The annual temperature ranges are, in general, smaller in the tropics, where the seasonal contrast in insolation is less than in higher latitudes. On the maps there are concentrations of isolines near the Tropic of Cancer. Similar concentration is, however, not so conspicuous in the map of annual range in air temperature, which responds less freely to the insolation than the ground temperature.

The annual temperature ranges are, generally, greater in continental than in oceanic climates. Siberia, with the highest index of continentality in the world, has an annual range in surface-soil temperature of over 45°C in places. Rapid temperature changes occur in the completely frozen ground, because it has a thermal diffusivity about 10–30 pct higher than the unfrozen ground [*Beskow*, 1935]. In summer, the long duration of sunshine in Siberia invites high temperature.

At Cape Chelyuskin the rate of the decrease of temperature range with depth tapers off abruptly at about ten cm depth. Both the summer heating in the 'active layer' of permafrost and the radiational cooling in winter appear to be limited to a thin layer.

At Ithaca, Resolute Bay, and Anchorage the annual ranges of air temperature exceed those in soil temperature in the top layers. This is the result of the insulating effect of snow cover in winter, preventing the lowering of soil temperature.

On the contrary, the soil-temperature range at shallow depths exceeds air temperature range in deserts; for example, Cairo, Tiflis, and along the mid-latitude west coasts having dry summers; for example, Seattle and Santiago. Dry, sandy soils with low heat capacity, such as occur in deserts, are more subject to temperature extremes than wet, heavy soils. At Seattle and Santiago the difference is caused by the relative coolness of the ocean air, which is brought in by prevailing westerlies.

At Santa Cruz the temperature range of soil is slightly larger at 30 cm than at 20 cm depth, according to ten years of records. Similar temperature profile curves are also found in a few other stations in Patagonia. In January the temperatures at Santa Cruz are practically the same in the top soil; in July they are 1.7°, 2.1°, and 1.6°C at 10, 20, and 30 cm depth, respectively. It seems that in July there is often a frozen layer at about 30 cm depth.

Stratum of invariable temperature—The temperature range decreases exponentially with depth. Theoretically, the temperature range for any point below the surface is given by

$$R_z = R_0 e^{-z\sqrt{\pi/aT}}$$

where R_0 and R_z are temperature range at surface and depth z, respectively; T is the oscillation period; and a the thermal diffusivity of the soil.

At a certain depth the temperature ranges finally become very small, say, less than 0.1°C. This depth, commonly called the 'stratum of invariable temperature,' varies with the climate and the thermal diffusivity of the ground.

Moisture content is the most important factor in determining the thermal diffusivity of a soil. The

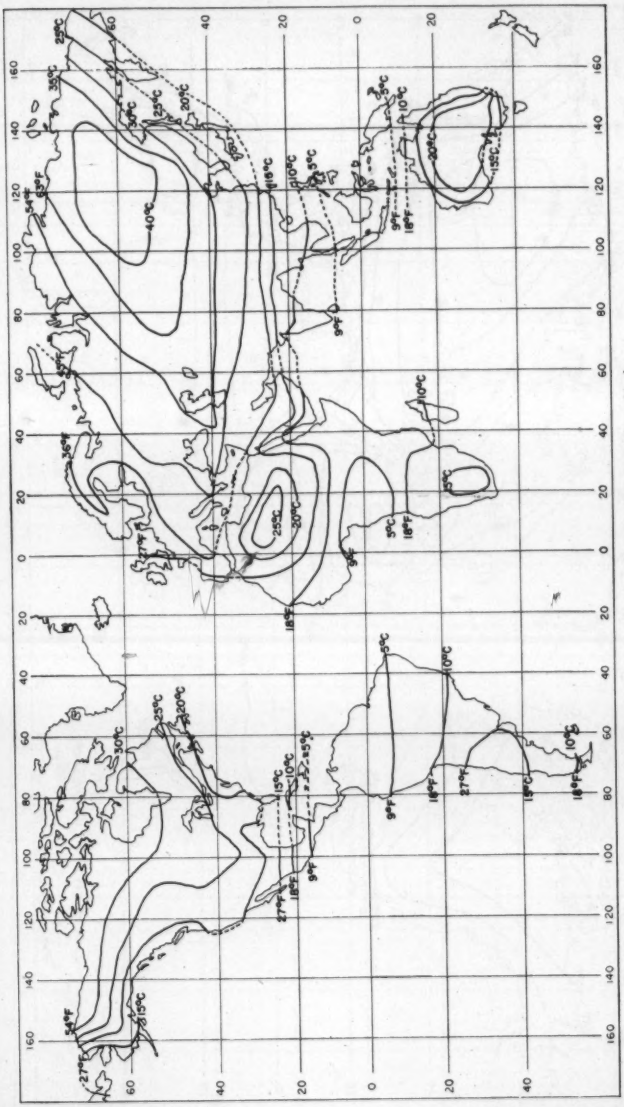

FIG. 1 – Annual range in soil temperature at 10 cm depth

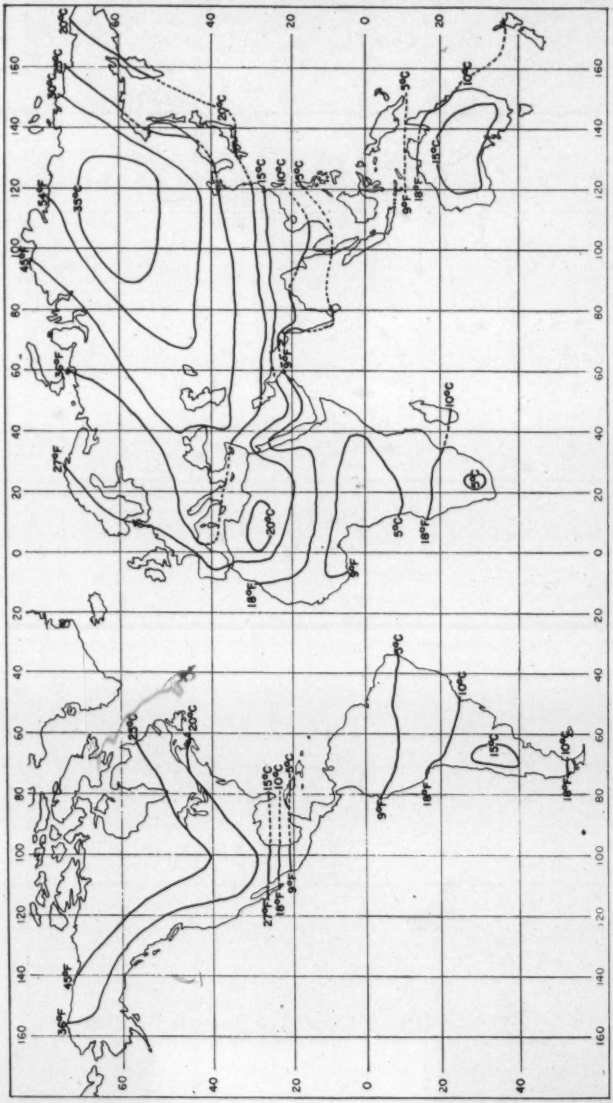

FIG. 2 – Annual range in soil temperature at 30 cm depth

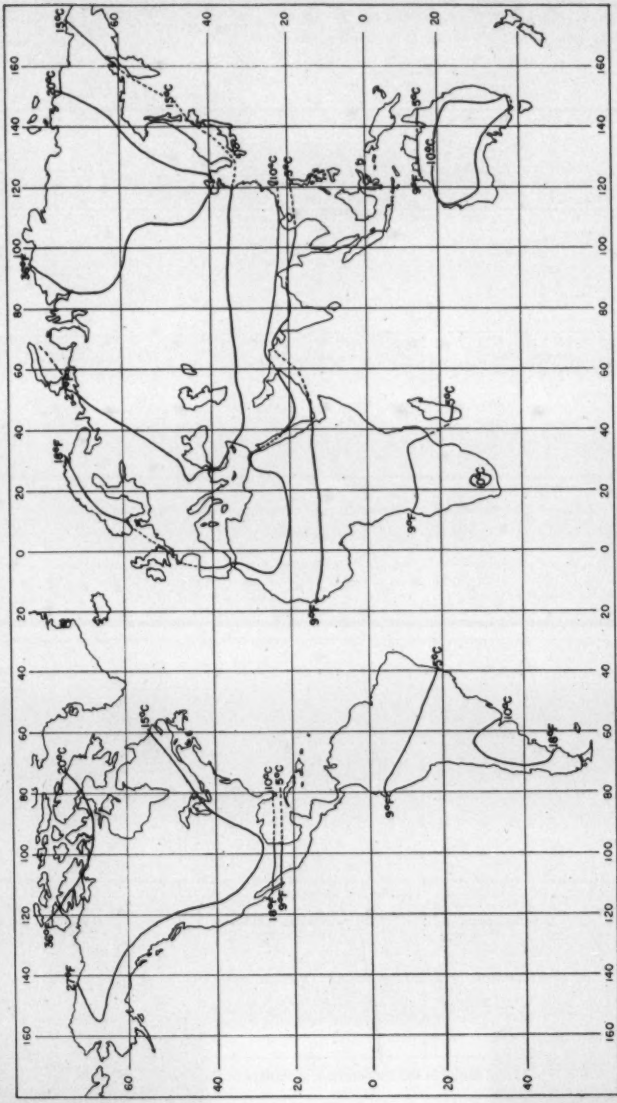

FIG. 3 – Annual range in soil temperature at 120 cm depth

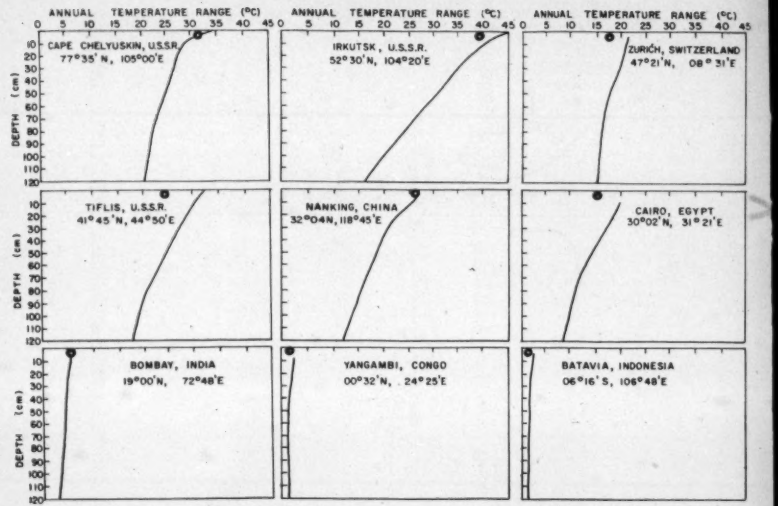

FIG. 4 – Annual range in soil temperature at stations in the eastern hemisphere

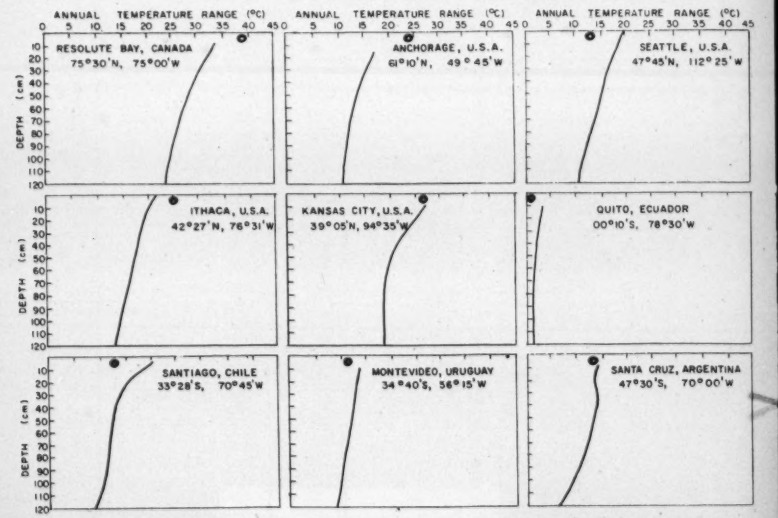

FIG. 5 – Annual range in soil temperature at stations in the western hemisphere

thermal diffusivity rises with a slight increase in moisture content and then falls off as more water is added [*Patton*, 1909]. Therefore, in a dry soil the temperature wave does not penetrate very far, but has a large range at the surface. In a moderately wet soil, although the temperature range at the surface is small, it penetrates deeply. The propagation of temperature wave in a thoroughly wetted soil is again rather limited.

Other things being equal, the stratum of invariable temperature is deeper in areas with a large surface temperature range. Observations by *Kandasamy* [1937], *de Morais* [1955], *Forbes* [1846], *Searle* [1953], *Leffingwell* [1919], *MacCarthy* [1952], *Thomson* and *Bremner* [1952], and others collected by the writer, seem to indicate that the stratum of invariable temperature lies at about 10 m in the tropics, 15 m in middle latitudes, and 20 m in the Alaska and northern Canada. The observational data agree with the calculated values if a value of 0.005 cm^2/sec is taken as the coefficient of thermal diffusivity in (1).

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Hydrologic Investigations at Hanford

J. R. Raymond and W. H. Bierschenk

Abstracts—During the twelve-year history of the Hanford Plant, several hundred wells were drilled throughout the area in order to obtain hydrologic, geologic, and radiologic monitoring data. Hydrologic data obtained throughout the Hanford site show that due to discharge to ground of about 28 billion gallons of non-radioactive process cooling water, the water table has locally been raised approximately 80 feet and that 20 miles southeast of the disposal sites it has been raised 0.5 foot. Pumping-test data indicate that locally the underlying aquifers may transmit as little as 30,000 gpd/ft and as much as 3,000,000 gpd/ft. Such hydrologic and hydraulic data are used to assist evaluation of safe radioactive waste disposal practices and to estimate effects of large volume nonradioactive process cooling water disposal.

Introduction—The United States Atomic Energy Commission's Hanford plutonium production plant is located in south-central Washington in a structural and topographic basin of volcanic rocks traversed by the Columbia River. The region is characterized by a low rainfall and a deep water table with a low gradient. Basaltic lavas and sedimentary interbeds of the Columbia River basalt series underlie the region. These volcanics are in turn overlain by a series of poorly consolidated lacustrine, fluviatile, and glaciofluviatile sediments.

The geologic and hydrologic features of the Hanford Works area are compatible with the disposal to ground of large volumes of uncontaminated process water, such as condenser cooling water. Criteria for the disposal to ground of process water containing radioactive isotopes have been developed to permit safe disposal through cribs of relatively smaller volumes of such wastes. Increased volume of these radioactive wastes and the economic incentive to avoid expensive permanent storage justified full exploitation of the ground as a disposal media. To insure that radioactive wastes can continue to be safely placed in the ground, an extensive hydrologic investigation is being carried out at Hanford. The primary objectives of this investigation are: (1) To determine the absolute ground-water contours and to follow the important changes produced by plant disposal to ground. (2) To measure ground-water direction and velocity in order to predict transit time to the Columbia River. (3) To determine hydraulic characteristics of aquifers such as the coefficients of transmissibility and storage. (4) To evaluate the capacity of the ground for safe disposal of radioactive wastes, taking into account the findings of the hydrologic study.

Figure 1 shows the general surface features, location of the area of interest, and the ground-water contour prior to plant influence in January 1944.

Field methods employed at Hanford—During the 12-year history of the project several hundred eight-inch cased perforated wells have been drilled to ground water. It is through these wells that most significant hydrologic, geologic, and radiologic monitoring data are obtained.

There are a number of more or less standard methods and techniques presently used in the hydrologic studies. These include: (a) The utilization of water-stage recorders for obtaining a continuous record of ground-water levels or for obtaining cyclic fluctuation data. (b) The routine measurement of water levels to permit contouring of the ground-water surface. From a series of these contour maps changes in ground-water velocities and directions of movement may be noted, and aquifer transmissibilities may be estimated. (c) The making of drawdown-recovery pumping tests at critical locations where accurate information on aquifer transmissibility and storage coefficients is needed. (d) The making of tracer tests at applicable sites in order to obtain more precise data on direction and rate of ground-water movement. (e) The employment of in-well techniques that are especially applicable at Hanford because of the extensive network of wells; for example the dilution-velocity test. This test consists of introducing an electrolyte into a well and measuring the electrical current flow between two electrodes in the well. Inasmuch as the current flow is proportional to the concentration of the electrolyte, as fresh water enters the well and electrolyte leaves, the current flow is reduced. This drop in current flow over a given period of time is used in an empirical equation to obtain a velocity value.

Figure 2 shows diagrammatically the essential features of the experimental arrangement. The

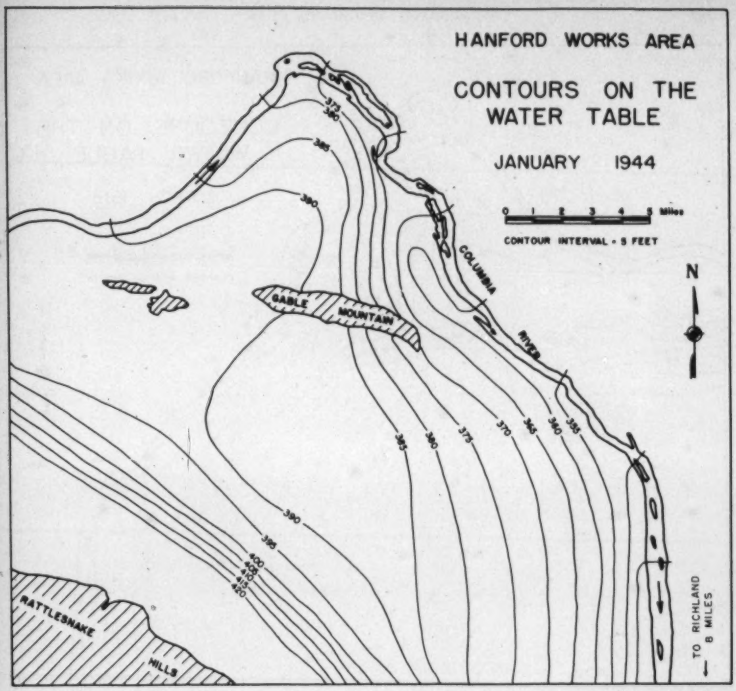

FIG. 1 – General surface features and ground-water contours prior to plant influence in January 1944

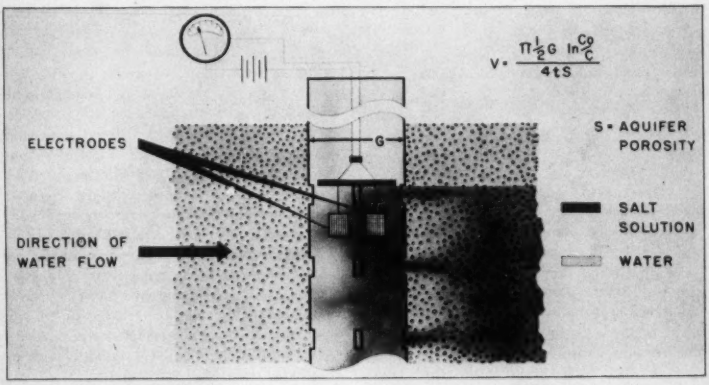

FIG. 2 – Schematic of the dilution-velocity method for determining ground-water velocities

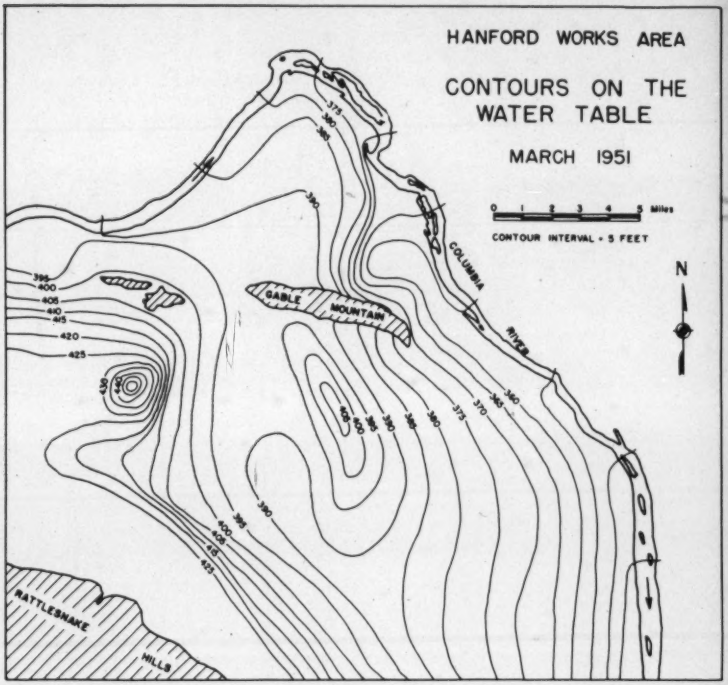

FIG. 3 – Contours on the water table, 1951, showing buildup of two ground-water mounds caused by large volume plant disposal

equation used to determine the velocity is as follows

$$V = \frac{\frac{1}{2}G \ln \frac{C_0}{C}}{4tS}$$

where V = Velocity
G = Well diameter
C_0 = Initial current flow
C = Current flow at time t
S = Aquifer porosity

Additional field studies for the immediate future include: (a) A geophysical survey using chiefly reflection seismic techniques to obtain information such as depth to bedrock and to the water table, and recognition of lithologic types. (b) The use of an in-well technique to determine the direction of ground-water flow through a well in addition to its velocity. It is comtemplated that a television camera be lowered down a well and subsequently a drop of dye be released in the water at the center of the well. As the dye moves with the water, it can be viewed on the television receiving screen a the ground surface; thus the direction and rate of ground-water movement can be determined.

Results of investigations—Contours on the water table, based on measurements in 94 wells at Hanford, show that the ground water originates in the mountainous areas of recharge to the southwest and moves in a general northeastward direction to the Columbia River. From the high areas of recharge the ground water descends outward for several miles at gradients of about 15 ft/mile.

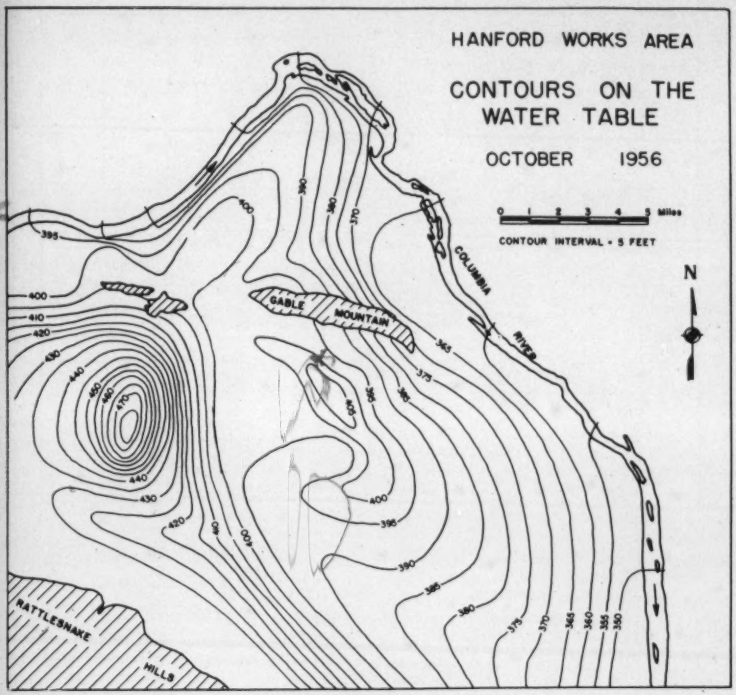

FIG. 4 – Contours on the water table, 1956, showing changes in the mounds due to changes in plant effluent disposal

Elsewhere the natural gradient is in the order of 5 ft/mile.

Appreciable changes have been made in the local and regional water table during 12 years of Hanford operation. Large volumes of process cooling water have been and are being discharged to several disposal swamps. To date, the total volume of all non-radioactive cooling water released to ground amounts to about 28 billion gallons. With the start up of the various plants and the consequent disposal of process water to ground, two major ground-water mounds were formed that by 1951 were 55 and 15 ft higher than the regional water table. Relative differences in the size and shape between these mounds are primarily due to differences in geologic controls; that is, differences in lithology and structure of the aquifers. In subsequent years the size and shape of the mounds fluctuated depending upon changes in operating procedures and volumes discharged. At the present time the mounds are approximately 80 and 20 ft above the natural water table. The progressive change in ground-water elevations near disposal sites is shown in Figures 1, 3, and 4.

Whereas the natural direction of movement of ground water is toward the Columbia River, the ground-water mounds locally reverse the normal hydraulic gradient. The directions of flow are radially off the crests of the mounds and thus part of the water flows in directions other than towards the river. As the rate of movement of the ground water is directly proportional to the hydraulic gradient, assuming homogeneity, the rising and falling of the ground-water mounds produces

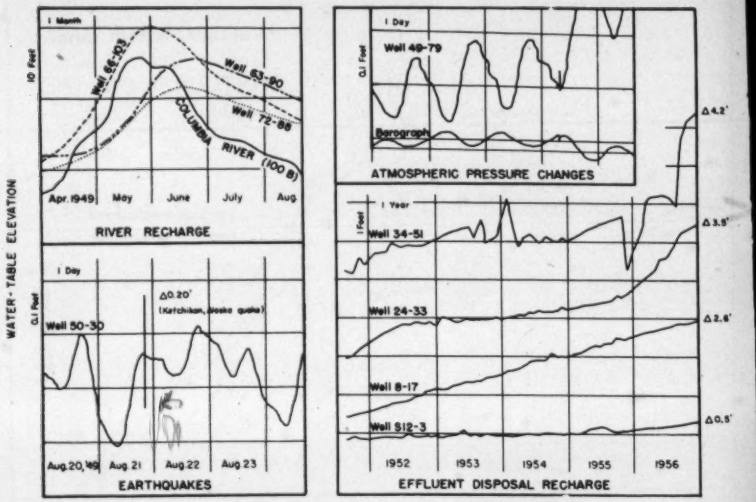

FIG. 5 – Hydrographs showing causes of water-table fluctuations

significant changes in the hydraulic gradient and consequently on the velocity of movement, a rising mound results in increased velocities in all directions. For example, the eastward gradient off the higher mound is presently about 30 ft/mile whereas in 1944 it was roughly 5 ft/mile in this vicinity; thus ground water beneath this area is probably moving about six times faster at the present than it did prior to plant operations.

Hydrographs of observation wells throughout the project show several principal types of fluctuations. Natural fluctuations are those showing (1) the periodic rise and fall of the water table in response to river stages, (2) diurnal changes in water level caused by changes in atmospheric pressures, and (3) small, though significant, fluctuations caused by regional and far-distant earthquakes. Artificial fluctuations are those responding to the variations in plant discharge to ground. Beneath, adjacent, and down gradient from areas of plant discharge a progressive rise of the water table has been noted. Immediately beneath discharge areas water levels have risen as much as 80 ft, but more significantly, water levels as much as 20 miles to the southeast have shown a progressive rise totaling about 0.5 foot, and all wells between have shown progressive rises in water level in rough proportion to their distance from the operating areas. Figure 5 is a series of hydrographs showing causes of water-table fluctuations.

Three pumping tests have been completed at Hanford which give an idea as to the magnitude of the hydraulic characteristics of the underlying aquifers. These characteristics, the coefficients of transmissibility and storage, are used primarily to determine the future effect on water levels in aquifers subject to recharge from the large volumes of process cooling water disposed to ground, and to give correlative quantitative data for estimating the time of passage of radioisotopes in the ground water between disposal sites and the Columbia River. The observed field data on drawdown and recovery in pumping wells and observation wells were combined with the Theis nonequilibrium formula to find the hydraulic characteristics. Recognizing that a few quantitative tests do not satisfy the demand for a quantitative study of a ground-water body, the following results, which are in general accord with the geology of the sites tested, give a reasonable idea as to the ability of the various aquifers to transmit and store water.

(a) A two-day drawdown-recovery test of the loose conglomerate of the Ringold formation gave a coefficient of transmissibility of approximately

30,000 gallons per day per foot (gpd/ft) and a coefficient of storage of about 7×10^{-5}.

(b) An eight-day test of part of the glaciofluviatile sediments north of Gable Mountain indicated a transmissibility coefficient of about 400,000 gpd/ft and a storage coefficient of 0.05.

(c) A four-day test of the very coarse-grained glaciofluviatile sediments south of Gable Mountain gave a transmissibility coefficient of 3,000,000 gpd/ft and a storage coefficient of 0.20.

Additional information as to the transmissibility of the Ringold aquifer containing the higher ground-water mound has been obtained by using a modified form of Darcy's law. The results indicated a transmissibility in the order of 25,000 gpd/ft.

As determined by dilution-velocity and tracer tests, corroborated by pumping-test results and suggested by the orientation of the elongate ground-water mound, there appear to be several areas of rapidly-moving water flowing in apparently preferred directions. These areas in which velocities of several hundred feet per day were measured lie south and north of Gable Mountain and southeastward of the eastern ground-water mound.

Conclusion—A continuing program is being carried out in hydrologic research with emphasis on determining more accurately the direction and rate of ground-water movement. Through development of this program, it is believed that maximum usage of ground waste disposal with no environmental hazards will be justified, resulting in overall economic gains in the operation of the plant.

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Underdrainage into Ditches in Soil Overlying an Impervious Substratum

HITOSHI FUKUDA

Abstract—Using conformal transformations, theoretical equations are derived for the quantity of water, in water-saturated soil, seeping per unit time, from a plane watertable into equally spaced ditches with vertical walls. An approximate theory is also given for ditches which do not have vertical walls. Several of the theoretical equations are tested experimentally and are found to be in agreement with the experimental results.

Introduction—Kirkham [1950] developed a theoretical solution for the quantity of water seeping from a plane water table into equally spaced ditches with vertical walls, just reaching or penetrating into an impervious soil substratum. This paper presents the case in which the ditches do not penetrate to the impermeable layer. Experiments are described that verify the theory.

Theoretical—In Figure 1, parallel ditches of width $2b$, depth d, spacing $2a$, and having vertical walls, are cut into soil of uniform permeability. The soil is of thickness h, and rests on an impervious layer. Rainfall or other water maintains the soil completely saturated. In order to determine the amount of water which seeps through the soil into a ditch, since the flow is same on each side of vertical planes to, and passing midway between the ditches, only the flow in the region between one such plane and an adjacent ditch, as OABCD, need be considered. Twice this amount of flow will be the seepage per ditch. It is further convenient to consider only the flow per unit length of ditch. Therefore OABCD may be considered as one face of a rectangular parallelopiped of unit thickness. It is assumed throughout that the ditches remove the seepage water rapidly so that the depth of water in the ditches is zero.

At first, for simplifying the mathematical treatment, the width of the ditches is assumed to be zero. In Figure 1 we take 0 as the origin of coordinates, OD as the x axis, and the y axis to be vertically upward. Accordingly we have for the flow region $x > 0$, $y < 0$.

If a potential φ is defined by

$$\varphi = y + \frac{p}{\gamma g} \tag{1}$$

where p, γ, and g are gage pressure, density of water, and the acceleration of gravity, respectively, it is known that φ satisfies Laplace's equation, namely

$$\frac{\partial^2 \varphi}{\partial x^2} + \frac{\partial^2 \varphi}{\partial y^2} = 0 \tag{2}$$

The velocity v (volume of water flowing through unit area perpendicular to the direction of flow in unit time) is related to the potential φ through Darcy's law

$$v = -\kappa \operatorname{grad} \varphi \tag{3}$$

where κ is the hydraulic conductivity and φ must satisfy the following boundary conditions

(i) At the soil surface, $y = 0$, $p = 0$, so $\varphi = 0$.

(ii) DC is a streamline; so at $x = a$, $\partial\varphi/\partial x = 0$

(iii) BC is a streamline, so at $y = -h$, $\partial\varphi/\partial y = 0$

(iv) AB is also a streamline, so at

$$x = 0, \qquad -h < y < -d, \qquad \partial\varphi/\partial x = 0$$

(v) On OA, $p = 0$, since it has been assumed that there is no water in the ditch; so at

$$x = 0, \qquad -d < y < 0, \qquad \varphi = y$$

Using conformal representation, z and ω are defined by

$$x + iy = z \tag{4}$$

$$\varphi + i\psi = \omega \tag{5}$$

where ψ is a stream function. The function ω is an analytic function of z.

Now, considering a function ζ defined by

$$\zeta = \partial\omega/\partial x \tag{6}$$

we find, since it is known in conformal representation that $\partial\psi/\partial x = -\partial\varphi/\partial y$, and since it is also known that Darcy's law applies

$$\zeta = \frac{\partial \varphi}{\partial x} + i\frac{\partial \psi}{\partial x} = \frac{\partial \varphi}{\partial x} - i\frac{\partial \varphi}{\partial y} = (-v_x + iv_y)/\kappa \tag{7}$$

Thus, ζ is a plane (Fig. 12, in the Appendix) with coordinates $-v_x/\kappa$, and v_y/κ, and we can map the region corresponding to the region OABCD of the z plane, on the ζ plane.

The results, finally obtained, are (see Fig. 11–17 in the Appendix),

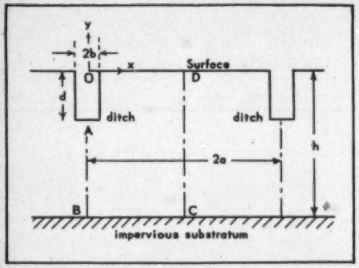

FIG. 1 – Vertical section through soil on an impervious layer and drained by equally spaced ditch drains

$$\zeta = -i - (2i/\pi)\{(E_1' - K_1')F(k_1, t_1) + K_1'E(k_1, t_1)\} \tag{8}$$

$$t_1 = i\sqrt{t_2} \tag{9}$$

$$t_2 = -\frac{1/k - t_A}{1/k + 1} \cdot \frac{t+1}{t - t_A} \tag{10}$$

$$t = \mathrm{sn}\{i(2K/h)z - K\} \tag{11}$$

where

$$K/K' = h/2a \tag{12}$$

$$t_A = \frac{\mathrm{cn}(2Kd/h)}{\mathrm{dn}(2Kd/h)} \tag{13}$$

$$k_1 = \sqrt{\frac{1/k + 1}{2} \cdot \frac{1 - t_A}{1/k - t_A}} \tag{14}$$

sn, cn, and dn are Jacobian elliptic functions defined in *Dwight* [1947, p. 168] (see also the Appendix) and $F(k_1, t_1)$, $E(k_1, t_1)$ in (8) are elliptic integrals of the first and second kind with modulus k_1, and defined respectively by

$$F(k_1, t_1) = \int_0^{t_1} \frac{dt_1}{\sqrt{(1 - t_1^2)(1 - k_1^2 t_1^2)}}$$

$$E(k_1, t_1) = \int_0^{t_1} \sqrt{\frac{1 - k_1^2 t_1^2}{1 - t_1^2}}\, dt_1$$

The symbols K_1 and E_1 are complete elliptic integrals with modulus k_1; and the K_1' and E_1' in (8) are the associated complete elliptic integrals.

Some special cases will now be considered.

Case 1, $a = \infty$—From (12), $K' = \infty$, $k = 0$, and the following equations are obtained

$$t_2 = -(t + 1)/(t - t_A) \tag{10'}$$

$$t = -\cosh \pi z/h \tag{11'}$$

$$t_A = -\cos \pi d/h \tag{13'}$$

$$k_1 = \cos \pi d/2h = \sin \pi/2 \cdot (1 - d/h) \tag{14'}$$

Next, to determine a velocity v_{y0} along the line OD, we introduce a symbol θ by the expressions

$$t_1 = -\sin \theta, \qquad t_2 = -\sin^2 \theta \tag{15}$$

Since $y(\zeta) = v_{y0}/\kappa$, we get

$$\frac{v_{y0}}{\kappa} = -1 + (2/\pi) \cdot \{(E_1' - K_1')F(k_1, \theta) + K_1'E(k_1, \theta)\} \tag{16}$$

and

$$t = (t_2 t_A - 1)/(1 + t_2) = \left(-1 + \cos \frac{\pi d}{h} \sin^2 \theta\right) \Big/ (1 - \sin^2 \theta)$$

and

$$\cosh \pi x/h = \cos \pi d/h + \left(1 - \cos \frac{\pi d}{h}\right) \Big/ \cos^2 \theta \tag{17}$$

Thus, (16) and (17) provide a relation between v_{y0}/κ and x through use of θ as a parameter. If we take $1 - d/h = 1/6, 2/6, 3/6, 4/6, 5/6$, that is, $h = 1.2d, 1.5d, 2d, 3d, 6d$ then, the corresponding calculated values of v_{y0}/κ are those shown in Tables 1 and 2.

For $x \gg h$, we get from (17) the relation

$$\cos^2 \theta = \frac{1 - \cos \pi d/h}{\cosh \pi x/h - \cos d\pi/h} = \frac{4 \sin^2 \pi d/2h}{e^{\pi x/h}}$$

Introducing the symbol ϵ by the relation

$$\theta = \pi/2 - \epsilon$$

that is, by

$$\epsilon = 2 \sin \frac{\pi d}{2h} \cdot e^{-\pi z/2h}$$

it is found that F and E are given by

$$F(k_1, \theta) = \int_0^{\pi/2 - \epsilon} \frac{d\theta}{\sqrt{1 - k_1^2 \sin^2 \theta}} \doteq K_1 - \epsilon/\sqrt{1 - k_1^2}$$

$$E(k_1, \theta) = \int_0^{\pi/2 - \epsilon} \sqrt{1 - k_1^2 \sin^2 \theta}\, d\theta \doteq E_1 - \epsilon \sqrt{1 - k_1^2}$$

TABLE 1—*Relation between seepage velocity at various distances from a ditch and depth of impervious substratum, $a = \infty$*

$h = 1.2\,d$		$h = 1.5\,d$		$h = 2\,d$		$h = 3\,d$		$h = 6\,d$	
$\frac{x}{d}$	$-\frac{v_{y0}}{\kappa}$	$\frac{x}{d}$	$-\frac{v_{y0}}{\kappa}$	$\frac{x}{d}$	$-\frac{v_{y0}}{\kappa}$	$\frac{x}{d}$	$-\frac{v_{y0}}{\kappa}$	$\frac{x}{d}$	$-\frac{v_{y0}}{\kappa}$
0	1	0	1	0	1	0	1	0	1
0.195	0.822	0.218	0.800	0.158	0.850	0.168	0.838	0.168	0.829
0.406	0.639	0.458	0.608	0.322	0.705	0.345	0.680	0.360	0.663
0.655	0.479	0.749	0.439	0.506	0.554	0.546	0.518	0.584	0.504
0.982	0.311	1.140	0.270	0.716	0.439	0.780	0.397	0.822	0.367
1.52	0.145	1.81	0.130	0.974	0.325	1.080	0.280	1.164	0.245
1.84	0.103	2.19	0.085	1.312	0.225	1.50	0.182	1.66	0.150
2.33	0.052	2.86	0.041	1.806	0.139	2.14	0.105	2.53	0.073
3.06	0.020	3.73	0.016	2.67	0.062	3.37	0.045	4.69	0.026
3.60	0.010	4.39	0.006	3.55	0.031	4.66	0.022	6.90	0.009
...	...	...	...	4.72	0.011	6.42	0.007	10.35	0.002

TABLE 2.—*Relation between seepage velocity at various distances from a ditch, $h = d$ and $h = \infty$, $a = \infty$*

$h = d$		$h = \infty$	
$\frac{x}{d}$	$-\frac{v_{y0}}{\kappa}$	$\frac{x}{d}$	$-\frac{v_{y0}}{\kappa}$
0	1	0	1
0.2	0.804	0.2	0.804
0.4	0.624	0.4	0.629
0.6	0.474	0.6	0.486
0.8	0.353	0.8	0.375
1.0	0.261	1.0	0.293
1.5	0.121	1.5	0.168
2	0.055	2	0.106
3	0.0115	3	0.051
4	0.0024	4	0.030
5	0.0005	5	0.0194
..	...	7	0.0101
..	...	10	0.0050
..	...	15	0.0022
..	...	20	0.0013

Whence we obtain finally

$$v_{y0}/\kappa \doteqdot -(2/\pi)\{(E_1' - K_1')/\sqrt{1-k_1^2} + K_1'\sqrt{1-k_1^2}\}\epsilon = (-4/\pi)(E_1' - K_1'\cos^2 \pi d/2h)e^{-\pi x/2h} \tag{18}$$

Values of v_{y0}/κ as given by (18) are tabulated in Tables 1 and 2 and graphed in Figure 2. The graphs are provided as they are needed for some graphical integrations to follow.

Case 2, $h = d$—Though here a method of conformal representation is useful, Fourier series may be more convenient, and the results are these obtained by *Kirkham* [1950], namely

$$\varphi = \frac{8h^2}{\pi^2}\sum_{m=0}^{\infty}\frac{(-1)^m}{(2m+1)^2}\cdot\sin\frac{(2m+1)\pi y}{2h}\cdot\frac{\cosh\frac{(2m+1)\pi(a-x)}{2h}}{\cosh\frac{(2m+1)\pi a}{2h}} \tag{19}$$

$$v_{y0}/\kappa = -\left(\frac{\partial\varphi}{\partial y}\right)_{y=0} = -\frac{4}{\pi}\sum_{m=0}^{\infty}\frac{(-1)^m}{(2m+1)}\cdot\frac{\cosh\frac{(2m+1)\pi}{2h}(a-x)}{\cosh\frac{(2m+1)\pi}{2h}a} \tag{20}$$

When $a \to \infty$

$$v_{y0}/\kappa \doteqdot -\frac{4}{\pi}\sum_{m=0}^{\infty}\frac{(-1)^m}{(2m+1)}\cdot e^{-(2m+1)\pi/2h)x} = -\frac{4}{\pi}\tan^{-1}e^{-\pi x/2h} \tag{20'}$$

If $x \gg h$

$$v_{y0}/\kappa \doteqdot -\frac{4}{\pi}\cdot e^{-\pi x/2h}$$

This relation is seen also in Figure 2 where the curves straighten out at large values of x.

Defining $Q/2$ as a flow from the region now considered, this flow should be equal to the total amount of water seeping into the soil surface, so utilizing (20′), we get the expression

$$Q/2\kappa = -\int_0^{\infty}\frac{v_{y0}}{\kappa}dx = \frac{4}{\pi}\sum_{m=0}^{\infty}\frac{(-1)^m 2h}{(2m+1)^2\pi} = \frac{8h}{\pi^2}(1 - 1/3^2 + 1/5^2 - \cdots)$$

That is

$$Q/2\kappa = 0.743h \text{ (when } a \to \infty \text{ and } h = d) \tag{21}$$

Case 3, $h = \infty$—Though the results of Case 1 can not be used here, we may obtain a solution starting with $h = \infty$ in the conformal mapping. We find, corresponding to (8), the result

$$\zeta = -i + i\sqrt{\frac{1-\cos\pi z/a}{\cosh\pi d/a - \cos\pi z/a}} = -i + i\frac{\sin(\pi z/2a)}{\sqrt{\cosh^2\pi d/2a - \cos^2\pi z/2a}} \tag{22}$$

The velocity at the soil surface is, then, in view of (7), found to be

$$v_{y0}/\kappa = -1 + \frac{\sin \pi x/2a}{\sqrt{\cosh^2 \pi d/2a - \cos^2 \pi x/2a}} \quad (23)$$

In particular, the velocity at the middle point between ditches, $x = a$, is

$$(v_{y0}/\kappa)_{x=a} = -1 + \frac{1}{\cosh \pi d/2a} \doteqdot \tfrac{1}{2}(\pi d/2a)^2 + \cdots \quad (23')$$

If after use of (6) we integrate (22), there results (since in (6) y = constant, and hence $\partial\omega/\partial x = \partial\omega/\partial z$) the expression (to within a constant of integration)

$$\omega = \varphi + i\psi = -i\left(z - \frac{2a}{\pi}\cos^{-1}\frac{\cos \pi z/2a}{\cosh \pi d/2a}\right) + C_1 \quad (24)$$

Here C_1, an integral constant, is zero because $z = -id$, $\varphi = -d$, and $\psi = 0$ at point A in Figure 1. Now, as we are taking $\psi = 0$ at D in Figure 1, the ψ value at an origin O is considered to be $Q/2\kappa$ and $z = 0$, $\varphi = 0$.

Thus, use of these values in (24) yields

$$\frac{Q}{2k} = \frac{2a}{\pi} \cdot \cos^{-1}\left(\frac{1}{\cosh \pi d/2a}\right) \doteqdot d\left[1 - \frac{1}{6}\left(\frac{\pi d}{2a}\right)^2 + \cdots\right] \quad (25)$$

the approximation being valid if $d/a \ll 1$.

Case 4, $h = \infty$, $a = \infty$—Putting $a \to \infty$ in (22), we obtain

$$\zeta = -i(1 - z/\sqrt{d^2 + z^2}) \quad (26)$$

and hence find

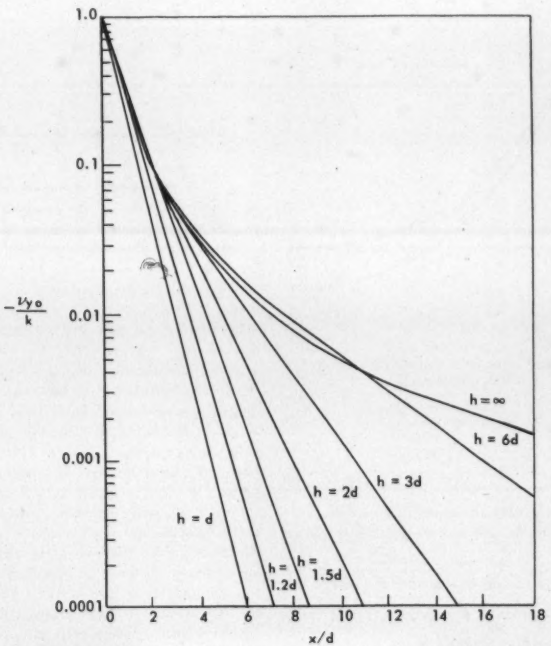

FIG. 2 – Seepage velocity at various distances from a ditch when, in Fig. 1, $a = \infty$

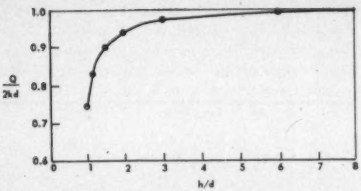

FIG. 3 – Seepage ratio and depth of the impervious layer when $a = \infty$

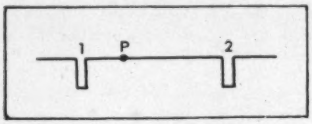

FIG. 4 – Two successive ditches

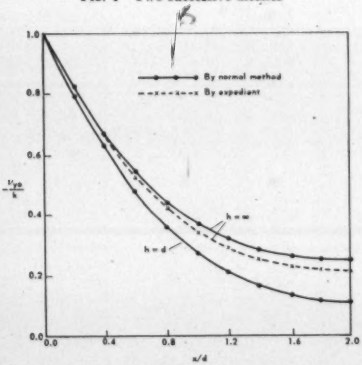

FIG. 5 – Seepage velocity at various distances from a ditch when $a = 2d$

$$v_{y0}/\kappa = x/\sqrt{d^2 + x^2} - 1$$
$$= -(\tfrac{1}{2})(d/x)^2 + (\tfrac{3}{8})(d/x)^4 + \cdots \qquad x \gg d \quad (27)$$

Some values of (27) are shown in Figure 2.

Utilizing (6) in (26) and integrating we obtain as before

$$\omega = \varphi + i\psi = i(\sqrt{z^2 + d^2} - z) \quad (28)$$

and use of $\varphi = 0$, and $\psi = Q/2\kappa$, at $z = 0$, yields

$$Q/2\kappa = d \qquad (\text{when } h = \infty \text{ and } a = \infty), \quad (29)$$

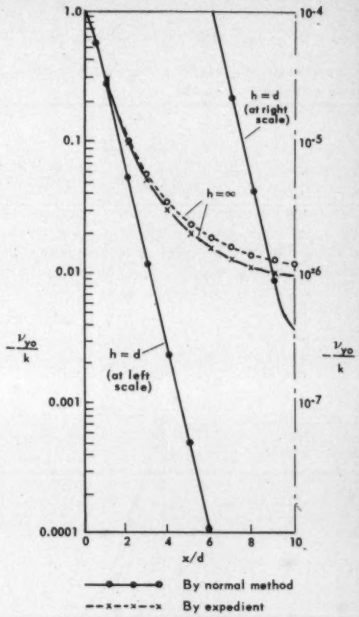

FIG. 6 – Seepage velocity at various distances from a ditch when $a = 10d$

agreeing with the approximation in (25), if we put there $a = \infty$.

Comparing (29) with (21), we can see that when $a = \infty$, the amount of flow for $h = d$ is about $\frac{3}{4}$ of that for the case that $h = \infty$. And though the general calculation of quantities for Case 1 is difficult, some values have been obtained by graphical integration utilizing Figure 2, and these values are presented in Figure 3. In the preparation of Figure 2 use was also made of (21) and (29).

Case 5, a and h are finite—Instead of making tedious calculations of the velocity by the general equations (8) to (14) when the values a and h are finite, we shall use an expedient. In Figure 4, v_1 is assumed to be a velocity at any point P at the soil surface, to be determined by (16), (17), (18) or Figure 2, when there is only a ditch (1) (Fig. 4) and $a = \infty$. And v_2 in Figure 4 is the velocity when only the ditch (2) is cut. With the ditches

thus considered individually, it is found that a value $v_1 + v_2$, (except when simultaneously $x = a$ and h is large) is nearly equal to a value of v_{y0} calculated by (8) to (14). Figure 5 and 6 show, respectively, for $a = 2d$ and $a = 10d$, the results obtained, when $h = d$ and $h = \infty$. In these Figures, we see that the expedient coincides with the normal method very closely when $h = d$, and that the expedient shows an error of about 20 pct at the mid-point between two ditches when $h = \infty$. But when $a \gg h$, the effect of ditches, as shown by (18), rapidly decreases exponentially, so we can expect to get satisfactory results by this expedient.

Correction for finite width of ditches—It would be difficult to determine analytically, seepage velocities for ditches of arbitrary width and rectangular bottoms as in Figure 1. We can, however, through introduction of a parameter λ, modify our previous solution such that it will apply approximately to the shape of a ditch in practice.

In the following we shall use subscripts one to denote quantities in the modified solution.

We suppose that the potential for the modified case is

$$\varphi_1(x, y) = \lambda\varphi \tag{30}$$

where φ is the potential function found before. We suppose further that (x_s, y_s) represents a point on the surface of the ditch. The surface might be as shown in Figure 7. Since the surface of the ditch is a surface of seepage, we must now have, instead of $\varphi = y$, the condition (the subscript s referring to points on the surface of the ditch)

$$\varphi_1(x_s, y_s) = y_s \tag{31}$$

We observe that the increase in size of a ditch from that of a slit to a finite width reduces the total friction encountered by the seeping water and also reduces the convergence of the flow. Accordingly, the potential $\varphi_1(x, y)$ is greater at all points in the flow medium than φ; and in (30) and in subsequent equations we have $\lambda \geqq 1$. Eq. (31) implies that the velocity at all points in the flow medium has been increased by a factor λ. When $\lambda = 1$ the ditches become slots of depth d and of infinitesimal width.

In continuing the analysis, we consider for simplicity, only the case $h = \infty$, $a = \infty$; whence, from (30) and (28) we have

$$\omega_1 = \varphi_1 + i\psi_1 = \lambda i\left(\sqrt{z^2 + d^2} - z\right) \tag{32}$$

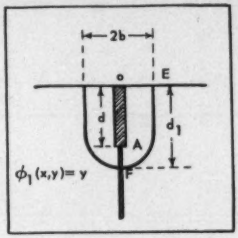

FIG. 7 – An elliptical ditch

In (32) let α and β be variables such that

$$\sqrt{z^2 + d^2} = \alpha + i\beta \tag{33}$$

Then, from (4), (32) and (33) we have

$$\omega_1 = \lambda i(\alpha + i\beta - z) = \lambda(y - \beta) + i\lambda(\alpha - x)$$

whence

$$\varphi_1 = \lambda(y - \beta) \tag{34}$$

$$\psi_1 = \lambda(\alpha - x) \tag{35}$$

and from (31) and (34) we obtain

$$y_s = \lambda(y_s - \beta) \tag{36}$$

From (3) we find for points on the surface of the ditch the expressions

$$\alpha^2 - \beta^2 = x_s^2 - y_s^2 + d^2, \qquad \alpha\beta = x_s y_s \tag{37}$$

But (36) yields $\beta = y_s(\lambda - 1)/\lambda$; whence the second of (37) becomes $\alpha = \lambda x_s/(\lambda - 1)$; and these latter two values when used in the first of (37) yield, after introducing the abbreviation

$$\mu = 1 - 1/\lambda$$

the result

$$\frac{x_s^2}{\mu^2 d^2/(1 - \mu^2)} + \frac{y_s^2}{d^2/(1 - \mu^2)} = 1$$

which is the equation of an ellipse with length of semi-axis in the x-direction $\mu\, d/(1 - \mu^2)^{\frac{1}{2}}$, and length of semi-axis in the y-direction $d/(1 - \mu^2)^{\frac{1}{2}}$.

Thus, in Figure 7, the semi-width b of the ditch is

$$b = \mu d/(1 - \mu^2)^{\frac{1}{2}} \tag{38}$$

and the depth d_1 of the ditch is

$$d_1 = d/(1 - \mu^2)^{\frac{1}{2}} \tag{39}$$

If $2b$ and d_1 are given, (36) and (37) may be solved for λ and d with the results

$$\lambda = d_1/(d_1 - b), \qquad d = (d_1^2 - b^2)^{\frac{1}{2}}$$

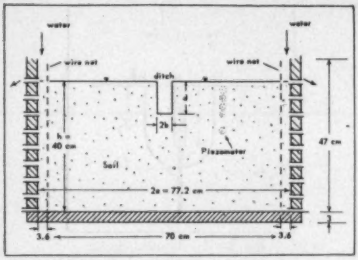

FIG. 8 – Apparatus for measuring seepage into a ditch

TABLE 3—*Texture of soil used in experiments*

Dia., mm.	>0.6	0.6–0.25	0.25–0.11	0.11–0.075	<0.075
Per cent	7.5	29.1	11.3	4.0	48.1

The discharge Q_1 can now be obtained. Instead of the condition $\psi = Q/2\kappa$ at $z = 0$ we now have $\psi_1 = Q_1/2\kappa$ at $z = b$. Accordingly, (35) becomes

$$Q_1/2\kappa = \lambda(\alpha - b)$$

where now

$$\alpha = \lambda x_s/(x - 1) = \lambda b/(\lambda - 1)$$

so that

$$Q_1/2\kappa = \lambda b/(\lambda - 1) = b/\mu$$

or using (38) and (39)

$$Q_1/2\kappa = d/(1 - \mu^2)^{\frac{1}{2}} = d_1 \qquad (40)$$

Eq. (40) is of particular interest because it shows that if $\mu < 0.3$, we have $1/(1 - \mu^2)^{\frac{1}{2}} \doteqdot 1$ and $d_1 \doteqdot d$ so that $Q_1 \doteqdot Q$. That is if $\mu < 0.3$, Q is nearly independent of the width of ditch.

Experimental—In order to check (21) and (29), a wooden box (Fig. 8), 77.2 cm long, 15 cm deep, and 40 cm high, one side of the box being a glass plate, was filled with sandy loam and a ditch was cut in the middle. The soil had the texture shown in Table 3. The soil was completely saturated to its surface by supplying water at two ends of the box, these ends subsequently being sealed. The water in the ditch was pumped up by a siphon. The quantity Q of this siphoned water entering into the ditch in unit time was measured by the same technique at the first five minutes for each of the experiments.

Test of Eq. (29)—To satisfy the conditions, $h = \infty$ and $a = \infty$ needed for (29), a ditch, 2.0 cm wide, was cut, varying its depth, with $h = 40$ cm, from $d = 2.5$ cm to $d = 10$ cm, and Q was measured. The results are shown in Figure 9, which show a linear relation between Q and d, and hence that the equation is correct. Note that the first points on the curve should be higher with respect to the straight line than the others (as they are), because the ditch is not of zero width, as is required for the validity of the equation $Q/2\kappa = d$. It is to be noted further that the conditions, which are also required, that $a/d \to \infty$ and $h/d \to \infty$, seem to have been realized sufficiently well: the experiments agreed with the theory even though $h = 40.0$ cm, $h - d = 37.5$ to 30 cm, $h/d = 16$ to 4, $a = 77.2/2 - 1.0 = 37.6$ cm, and $a/d = 37.6/10$ to $37.6/2.5$, that is, $a/d = 3.76$ to 15.04. The fact that $a/d = 3.76$ to 15 serves, within experimental errors, for $a/d = \infty$, will be utilized below.

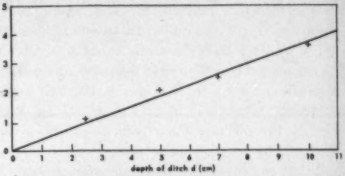

FIG. 9 – Experimental test of seepage versus depth of ditch ($2b = 2.0$ cm)

As another method of testing the equation $Q/2\kappa = d$, the hydraulic conductivity κ was calculated to be 3.09×10^{-3} cm/sec at $d = 10$ cm and $Q = 3.7$ cc/min in Figure 9; on the other hand, the measured value of κ was found to have the value 4.4×10^{-3} cm/sec, for points near the ditch. Considering errors in the experimental technique, the difference between these two values of κ may be supposed to be inevitable. Thus (29), $Q/2\kappa = d$ may be considered to have been proved to be correct also by the conductivity measurements.

Test of Eq. (21)—To satisfy the conditions of $h = d$ and $a = \infty$, a ditch 2.0 cm wide and of variable depth (but with $d \gtrsim 5$ cm) was cut so that its bottom could coincide with the impervious layer. For $a = \infty$, the condition $a = 37.6$ cm was used. The value of Q was determined for several different values of $h = d$ as well as for several values of $h/d > 1$ and the results are shown in the upper part of Figure 10. Here the upper curve shows measured values of Q, and the lower curve shows the ratio of Q to a value

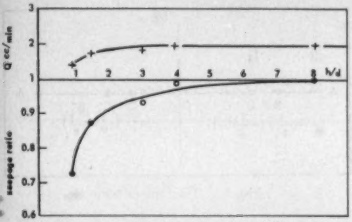

FIG. 10 – Upper curve: experimental values of seepage versus depth of impervious layer; lower curve, seepage ratio (see text) versus depth of impervious layer (a = 37.6 cm, d = 5.0 cm)

TABLE 4.—*Effect of distance between ditches on seepage (see Eq. 25)*

Distance between ditches ($2a$)	$2d$	$3d$	$5d$	$10d$
$\frac{4}{\pi}\left(\frac{\pi d}{2a}\right)^2$	0.41	0.18	0.066	0.016

of Q when $h = \infty$. The experimental data are again in agreement with the theory.

We see that the ratio, 0.72, when $h = d$, is very close to the theoretical value 0.743. Also, when the impervious layer lies at a depth more than two times the depth of the ditch, we see that the amount of seepage, in accordance with the theoretical curve, is more than about 90 pct of that for the case $h = \infty$. It is concluded that (21), $Q/2\kappa = 0.743\ h$, is correct.

Test of Eq. (25)—In the experiments described above we had, a = 37.6 cm and d = 2.5 to 10 cm so that if we use the data in (25) (for which $h = \infty$), we will have for the second term in the infinite series $(\frac{4}{\pi})(\pi d/2a)^2 = 0.002$ to 0.03. Thus, it is concluded, for our experiments, that the effect of the distance between ditches on the seepage is negligible. Table 4 has also been prepared to show that the effect of spacing on Q is small when the spacing is several times the depth. When the spacing is ten times the depth ($2a = 10d$), an increase of the spacing to infinity would not change Q by more than 1.6 pct.

APPENDIX

This is with reference to the mathematical details which relate to (8) to (14), by means of Schwartz-Christoffel theorem.

A hodograph transformation [*Muskat*, 1937, p. 300] is first made. On OA in Figure 11, $\varphi = y$,

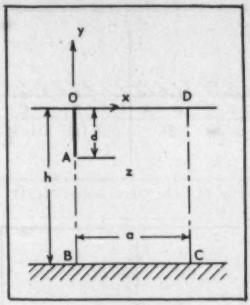

FIG. 11 – The z plane representation of underdrainage into a ditch

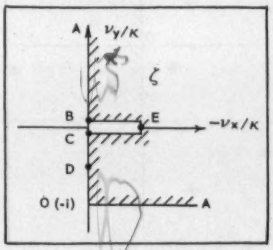

FIG. 12 – The ζ plane map of Fig. 11

so $\partial\varphi/\partial y = 1$. Also, in view of (7), an imaginary part of ζ is -1, and OA corresponds to OA in Figure 12, the corresponding points on z and ζ planes have the same letters. At origin 0, $\partial\varphi/\partial x = 0$, so $\zeta = -i$. As a velocity becomes infinite at point A, A corresponds to $\zeta = \infty$.

On OD and DC in Figure 11, flow is vertically downward, so $\partial\varphi/\partial x = 0$. And at C, the velocity is zero due to the bending of a streamline at a right angle, so C corresponds to $\zeta = 0$. Therefore ODC is between $\zeta = -i$ and $\zeta = 0$ on the part of the imaginary axis.

On CB in Figure 11, as a stream is horizontal, C and B are on the real axis; but due to the velocity being zero ($\zeta = 0$) at C and B, one is considered to be on the ζ plane, on the way from C to B via an as yet unknown point E on the real axis.

On BA in Figure 11, as the velocity is vertically upward, BA corresponds to the upper half of the imaginary axis.

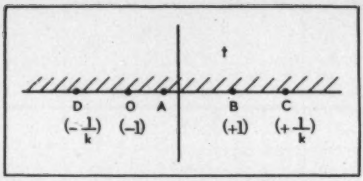

FIG. 13 – The t plane map of Fig. 11

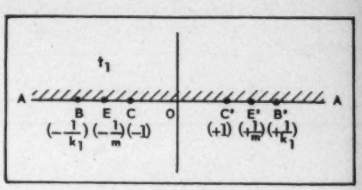

FIG. 15 – The t_1 plane map

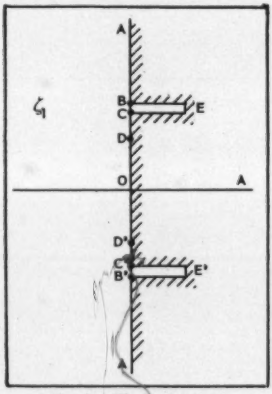

FIG. 14 – The ζ_1 plane map

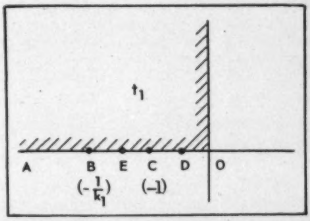

FIG. 16 – The t_1 plane map

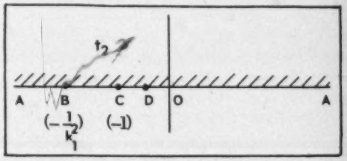

FIG. 17 – The t_2 plane map of Fig. 16

Thus, the region of the z plane (Fig. 11) corresponds to a shaded portion on ζ plane (Fig. 12).

Since ζ is an analytic function, when $\zeta = \zeta(z)$ is known by the above correspondence between z and ζ planes, a velocity ζ at any point z is obtainable.

Now we map the z plane on a new plane t (Fig. 13), taking D, O, B, and C $-1/k$, -1, $+1$ and $+1/k$ respectively on the real axis of t (k is modulus of Jacobi's elliptic function, and $k < 1$). By means of Schwarz-Christoffel theorem, we have a mapping function [*Muskat*, 1937, p. 197]

$$Z = c_1 \int_0^t \frac{dt}{\sqrt{(1-t^2)(1-k^2t^2)}} + c_2$$

or using Jacobi's elliptic function [*Whittaker* and *Watson*, 1920; *Byrd* and *Friedman*, 1954]

$$t = \mathrm{sn}(cz + c')$$

as $z = 0$ corresponds to $t = -1$,

$$-1 = \mathrm{sn}c' \qquad c' = -K$$

and $z = -ih$ corresponds to $t = +1$, so

$$+1 = \mathrm{sn}(-K - ic_4 h) \qquad c_4 = i(2K/h)$$

$$t = \mathrm{sn}\left(i\frac{2K}{h}z - K\right) \tag{41}$$

here $z = a$ corresponds to $t = -1/k$, so

$$2Ka/h = K' \qquad K/K' = h/2a \tag{42}$$

which gives a value k. And A ($z = -id$) corresponds to

$$t_A = \mathrm{sn}(2Kd/h - K) = -\frac{\mathrm{cn}(2Kd/h)}{\mathrm{dn}(2Kd/h)} \tag{43}$$

Considering $\zeta_1 = \zeta + i$, a shaded portion on ζ_1 plane is mapped on the upper half of t_1 plane (Fig. 14 and 15), here we have

$$\zeta_1 = c \int_0^{t_1} \frac{1 - m^2t_1^2}{\sqrt{(1-t_1^2)(1-k_1^2t_1^2)}}\,dt_1$$

$$0 < k_1 < m_1 < 1$$

considering E as $t_1 = -1/m$. Transforming ζ_1, c being a constant

$$\zeta_1 = c\left\{\int_0^{t_1} \frac{dt_1}{\sqrt{(1-t_1^2)(1-k_1^2t_1^2)}} - \frac{m^2}{k_1^2}\int_0^{t_1} \frac{k_1^2t_1^2\,dt_1}{\sqrt{(1-t_1^2)(1-k_1^2t_1^2)}}\right\}$$

$$= c\left\{\left(1-\frac{m^2}{k_1^2}\right)\int_0^{t_1} \frac{dt_1}{\sqrt{(1-t_1^2)(1-k_1^2t_1^2)}} + \frac{m^2}{k_1^2}\int_0^{t_1}\sqrt{\frac{1-k_1^2t_1^2}{1-t_1^2}}\,dt_1\right\}$$

$$= c\left\{\left(1-\frac{m^2}{k_1^2}\right)F(k_1, t_1) + \frac{m^2}{k_1^2}E(k_1, t_1)\right\} \quad (44)$$

Here $F(k_1, t_1)$, $E(k_1, t_1)$ are elliptic integrals of the first and second kind with modulus k_1 respectively. As $t_1 = 1$ corresponds to $\zeta_1 = -i$

$$-i = c\left\{\left(1-\frac{m^2}{k_1^2}\right)K_1 + \frac{m^2}{k_1^2}E_1\right\} \quad (45)$$

K_1, E_1 being complete elliptic integrals with modulus k_1. Also $t = 1/k_1$ corresponds to $\zeta_1 = -i$, so (see *Whittaker* and *Watson* [1920], p. 502 and p. 530, example 3, observing that E in Whittaker and Watson is expressed in terms of a different variable than here)

$$-i = c\left\{\left(1-\frac{m^2}{k_1^2}\right)(K_1 + iK_1') + \frac{m^2}{k_1^2}[E_1 + i(K_1' - E_1')]\right\} \quad (46)$$

Also we get from (45) and (46)

$$i\left(1-\frac{m^2}{k_1^2}\right)K_1' + i\frac{m^2}{k_1^2}(K_1' - E_1') = 0$$

$$m = k_1\sqrt{K_1'/E_1'} \quad (47)$$

then putting (47) in (45),

$$-i = c\{(1 - K_1'/E_1')K_1 + (K_1'/E_1')E_1\}$$

Considering Legendre's relation

$$EK' + E'K - KK' = \pi/2,$$

we determine

$$c = -iE_1'/(\pi/2) \quad (48)$$

putting (47) and (48) in (44), we get

$$\zeta_1 = -2i/\pi\{(E_1' - K_1')F(k_1, t_1) + K_1'E(k_1, t_1)\} \quad (49)$$

As the second quadrant only of the t_1 plane corresponds to the region now under consideration (Fig. 16), taking $t_1 = i\sqrt{t_2}$ this region is mapped on the upper half of t_2 plane (Fig. 17) in which $B(t_1 = -1/k_1)$ corresponds $t_2 = -1/k_1^2$.

At last, the t_2 plane is mapped on the t plane. Putting $t_2 = \alpha(t+1)/(t - t_A)$ (α is a constant) or substituting in the bilinear transformation formula as given in *Green* [1948, pp. 86–87], we see, as $t = 1/k$ corresponds to $t_2 = -1$, that $\alpha = -(1/k - t_A)/(1/k + 1)$ so

$$t_2 = -\frac{\frac{1}{k} - t_A}{\frac{1}{k} + 1}\,\frac{t+1}{t - t_A} \quad (50)$$

In (50), since $t = +1$ for $t_2 = -1/k_1^2$, we get

$$k_1 = \sqrt{\left(\frac{1}{k} + 1\right)}{2} \cdot \frac{1 - t_A}{(1/k) - t_A} \quad (51)$$

from which k_1 is determined, t_A being known from (43) and k from (42). Thus all equations from (8) to (14) have been derived.

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Evaporation Suppression from Water Surfaces

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Abstract—Techniques used for measuring the effect of monomolecular films to suppress evaporation from water surfaces are reviewed. A brief history of chemical studies and field testing of organic compounds is presented. Research in Illinois by the State Water Survey indicates that normal evaporation may be reduced by as much as one-third by efficient use of monolayers.

Introduction—Hydrologic phenomena are extremely variable in their intensity, quantity, and time of occurrence. The more apparent factors such as rainfall and runoff have received much study, while equally important phenomena such as evaporation have been accorded comparatively little attention. Evaporation is an important factor from the water supply standpoint and in recent years many scientists all over the world have been experimenting on means to reduce this direct water loss. Since 1952 the Australian Commonwealth Scientific and Industrial Research Organization (CSIRO) has been testing an insoluble chemical film to suppress evaporation from small water surfaces. W. W. Mansfield, Physical Chemist, for whom the Australian process has been named, is the first man credited with developing the idea of using hexadecanol, which comes from whale oil, for reducing evaporation losses from small ponds. One-eighth inch diameter beads of this material were fed to the water from specially constructed rafts and a monomolecular skin covering formed which reportedly reduced evaporation up to 45 pct. Recently *Commonwealth Scientific and Industrial Research Organization* [1956] published a paper which reports that 25 pct of the water lost normally by evaporation could be saved.

An article by *Laycock* [1956] describes the work done by the East African Meteorological Department with cetyl alcohol (hexadecanol). An earlier article [*Anonymous*, 1955] stated that D. A. Davies, Director at the Nairobi Meteorological station, had been able to reduce evaporation 50 to 70 pct from four-foot diameter pans of water by using hexadecanol. Laycock indicated that fine copper-mesh anchored basket rafts are located one to each acre on the Nairobi reservoir of over 88 acres, with a capacity of 400,000,000 gal. In East Africa annual water losses through evaporation generally amount to six feet and in some cases are reported to be as great as ten feet. Australian figures also indicate evaporation losses up to ten feet. The published data indicate monthly savings of water from 15 to 24 pct on the African lake. The Australians report that their method of saving water is presently effective only in reservoirs up to two acres in area.

Properties required in a suppressant—An effective evaporation suppression agent must possess several characteristics. From the standpoint of the water for domestic use, it must be non-toxic and easily handled. It should be in a form that is readily applied to the reservoir surface and the cost should be reasonable. It must be sufficiently pure so as not to cause any taste problems in the finished water nor should it prevent proper treatment of the water.

The water conservationist is primarily interested in the ability of the agent to suppress evaporation in a lake. The substance must be lighter than water so that it will float but not be overly soluble. The film must spread easily and re-form readily after being broken by wave action or passage of boats. It must remain operative during the months of greatest potential evaporation. Fishermen have a question: what will such a covering do to aquatic life? Any film must be able to let oxygen into the water and be non-toxic to fish and other aquatic life. Lastly the covering must be invisible and odorless so that lake users will be neither aware of nor annoyed by its presence.

Chemical studies—Physical chemists have been carrying on studies with monomolecular layers for reducing losses from water surfaces for over forty years. *Langmuir* [1917] screened many samples of chemical compounds for their abilities to retard evaporation under laboratory conditions. *Hedestrand* [1924] tried using dilute benzene spreading solutions on water surfaces over which currents of air were moving. His experimental system led him to the conclusion that such films had little effect on the rate of water evaporation. *Rideal* [1925], on the other hand, showed that stearic acid monolayers greatly reduced evaporation but his analysis did not permit quantitative results. *Sebba* and *Briscoe* [1940] determined that the decrease in evaporation rate caused by monolayers was a function of surface

pressure. *Langmuir* and *Schaefer* [1943] devised a technique for measuring evaporation resistance. They suspended a solid desiccant above the water surface and measured the amount of water evaporated by a stream of dry air blown over the surface film. The resistance to evaporation is represented as an energy barrier related to the film pressure. *Rosano* and *La Mer* [1956] carried on studies of evaporation rates through monolayers of esters, acids, and alcohols.

Field research in the United States—In the United States, research in evaporation suppression has been carried on by federal, state, and private organizations in addition to the studies by physical chemists. The United States Bureau of Reclamation and the United States Geological Survey have both made fundamental studies on energy balance and film spreading techniques and several laboratory studies of evaporation savings. A team of North Texas State College students in collaboration with six government agencies has conducted studies on physical and biological effects of hexadecanol in a five-acre lake near Oklahoma City. The Southwest Research Institute has a program of research on control of evaporation from reservoirs in Texas.

The Illinois program—The work of the Illinois State Water Survey in this field has been concentrated on the measurement of differences in evaporation rates from pairs of identical water containers where one surface is unprotected and the second surface has a coating of hexadecanol. These studies have also been applied to a 100,000-gallon capacity tank.

The Survey operates three evaporation stations, in northern, central, and southern Illinois. These are Class A pan installations and Stevens-Roberts evaporimeters [*Roberts*, 1954] which record water losses graphically from a three-square foot surface. In February 1956, two identical evaporimeters Figure 1, were installed at the Survey's Urbana evaporation station. One was seeded with one milligram of hexadecanol; the second had water without any protective coating. The water containers were approximately two feet in diameter and one inch deep with built-in overflows to waste excess precipitation. During the spring and early summer months the effect of the monolayer cover was negligible, but there were individual days during July and August when the pan with the hexadecanol cover had water loss of nearly 30 pct less than the pan without the chemical cover. Figure 2 shows the cumulative evaporation from both pans for the period July 1 to September 20, 1956. The average reduction in evaporation was ten per cent for the period.

FIG. 1 – Evaporimeters at Urbana, Illinois, evaporation station

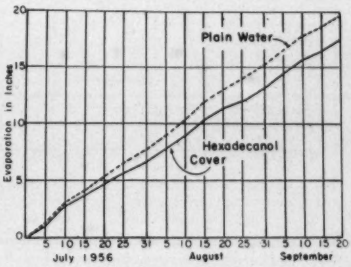

FIG. 2 – Cumulative evaporation from evaporimeter pans at Urbana, Illinois

In June 1956, two 55-gallon drums, with one end of each removed, were buried adjacent to each other at the evaporation station. The open ends of the drums extended two inches above the ground surface. Angle-iron supports for hook gages were constructed across the open ends and the pans were filled with water to the ground level. Thermocouples were inserted just below the water surfaces to give continuous measurements of water temperatures in each of the containers. One was filled with plain water and the second was given an application of one mg of hexadecanol. Once-daily readings with hook gages were made on both pans. Water losses from the two drums for the period July 1 to September 20, 1956 differed by 27 per cent loss as shown in Figure 3. After each two weeks of oper-

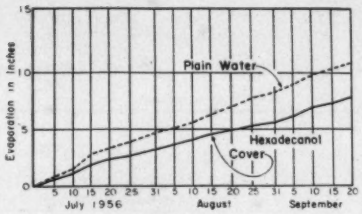

FIG. 3 – Cumulative evaporation from three-foot deep buried pans at Urbana, Illinois

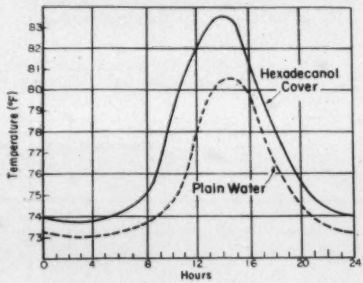

FIG. 4 – Surface water temperature curves for three-foot deep buried pans one day after application of hexadecanol

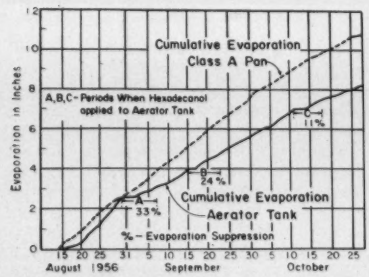

FIG. 5 – Evaporation from Class A pan and 100,000-gallon aerator tank at Urbana, Illinois

ation the drums were drained, cleaned, and refilled with water, and the experiment repeated with the treatment reversed to counterbalance any local effect of exposure. Similar data were obtained. One minor aspect of the study is the increase in surface temperature of the treated water as compared with the untreated surface. A study of the thermograph traces for the days after the pans were treated with hexadecanol indicated that at the warmest time of the day, when evaporation would be greatest, the water directly under the monolayer surface was two to five degrees F warmer than the plain water (Fig. 4).

Although hexadecanol films are reported [*Anonymous*, 1956] to allow the free transfer of oxygen and carbon dioxide from the air through the film to the water, there was some evidence that the film had a retarding effect. Rust collected along the inside of the drum filled with plain water to a depth of six inches from the surface while less than one inch of rusting was noted in the drum that had the monolayer covering.

In August 1956 the University of Illinois made available for this project a 100,000-gallon capacity aerator tank 30 ft in diameter and 14 ft deep located on the campus of the University at Urbana. During August–October, tests were made for water losses from this, using alternately plain water surfaces and surfaces with monolayers. The water was changed before each treatment began. Figure 5 shows the cumulative evaporation from the aerator tank and from a nearby Class A pan.

During the periods marked A, B, and C the aerator water surface was treated with hexadecanol. For the week of August 30 to September 7, evaporation from the aerator tank was 33 pct less than normal and was credited to the evaporation suppression effect of hexadecanol. Similar credits of 24 pct and 11 pct are shown for the periods September 14 to 23 and October 11 to 18. It can be seen that the evaporation suppression effect of the chemical becomes less as summer ends and fall weather begins. Sampling of the interim periods indicates close agreement between pan and aerator tank evaporation rates.

Examination of the lower curve shows that efficiency of the chemical was highest during the first two or three days of application and dropped considerably during the latter part of each period. This trend may indicate that the methods of applying the chemical and of maintaining its effectiveness should be improved.

Figure 6 shows one section of the aerator tank including the hook gage, temperature recorder, and the water-level recorder.

Cost of retarding water evaporation—The small quantity of chemical used so far in the Illinois research program has cost $2.10 per 500 grams, roughly $2.00 per pound. The Australians report their cost for hexadecanol as 7s per pound or about

75 cents. The evaporation retardant material used in the Texas studies was reported to cost 40 cents per pound.

Dressler [1956] points out that the film-forming material accounts for two-thirds the cost of evaporation-control treatment; the remaining one-third to getting the chemical on the water. The results of several research projects throughout the world indicate that the water saved is worth 20 or more times the cost of treatment, with indications that greatest savings could be effected if the treatment can be applied on larger water bodies.

Applying the film—A total of four hexadecanol distributors, shown in Figure 7, was used on the Illinois Water Survey's aerator tank. The distributors had wooden bases ten inches long and wooden ends 4 x 4 inches. The sides and tops were made of 12-mesh copper screen wire. The wire mesh floating container, one anchored in each acre of water area, has been the popular means in Australia, Africa, and the United States for getting the film on the water. This method of propagation is probably unsuitable for large-scale control of evaporation from lakes where there is considerable boat traffic.

It is suggested that boats could be one means of applying the monolayer to Illinois lakes and water-supply reservoirs. On most large lakes a police boat regularly patrols the waters. A simple attachment on the water pump of the boat engine would channel a stream of water through a vessel containing the chemical and into the lake. The chemical would be spread by the wake of the boat and the area and schedule of seeding could be adjusted to the needs of the individual lakes. The program cost would be little more than the cost of chemicals. The labor expense would be absorbed in the cost of operating the patrol boat. A few floating distributors may be necessary on the windward sections of the lakes to insure maximum effect of the monolayer. (Since preparing this manuscript continued research has developed additional methods of applying the film. During the summer and fall of 1957, tanks containing mixtures of powered hexadecanol and protective chemicals in water solution were used to produce strong films on a five-acre lake in central Illinois. Data from this part of the research are not complete.) As the value of monolayer coverings becomes better known in the field of water resources management, the problems of developing practical and economical methods of producing the coverings will probably be quickly developed.

Toxicity and attrition of films—According to

FIG. 6 – View of test equipment at the 100,000-gallon aerator tank

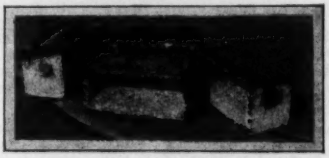

FIG. 7 – Hexadecanol distributors

Bernard Berger (personal communication), film destruction by organisms in a well-seeded natural water may be an important factor. *Ludzack* and *Ettinger* [1956] have found that emulsions of hexadecanol and pellets of the material suspended in baskets have been observed to undergo biological destruction in laboratory test studies. They report that on two different runs at 20°C suspensions of hexadecanol in very gently aerated carboys showed a weight loss averaging $3\frac{1}{4}$ and $4\frac{1}{8}$ pounds per acre per week.

The non-toxicity of commercial preparations containing hexadecanol, as determined by the Robert A. Taft Sanitary Engineering Center, was accepted as a basis for Illinois tests, in the absence of direct evidence against hexadecanol as a hazard to health.

Conclusions—Although the Illinois State Water Survey evaporation suppression study has been in operation only a year, a literature search indicates that our experiences in this study confirm much that has been found experimentally elsewhere although our findings appear to be generally more conservative. Most of the studies have been carried on in areas of the world where normal evaporation amounts are two or three times greater than those observed in Illinois. Under Illinois conditions our studies indicate that the rate of natural water loss by evaporation may be reduced by a maximum of 33 pct during the warmest part of the summer and

by about 11 pct during the cooler frost-free periods by application of hexadecanol. Many Illinois water-supply reservoirs store nearly 50 pct of their capacity in the top three feet. Normal evaporation exceeds three feet per year in reservoirs in the southern half of the state where surface waters provide most municipal supplies. Assuming full reservoirs, if evaporation could be reduced by one-third it would be equivalent to a 17-pct increase in Illinois reservoir storage capacity.

During the summer of 1957, the program was expanded to include studies on suppressing evaporation from larger water bodies and of problems encountered so far in our work in Illinois.

Acknowledgments—This report was prepared under the general supervision of H. F. Smith, Head, Engineering Subdivision, and William C. Ackermann, Chief of the Illinois State Water Survey.

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Illinois State Water Survey, Urbana, Illinois

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The Thickness of Lemon Creek Glacier, Alaska, as Determined by Gravity Measurements

E. THIEL, E. LACHAPELLE, AND J. BEHRENDT

Abstract—The gravity method of geophysical exploration has been employed to determine the thickness of a valley glacier. One hundred and eighty-two gravity stations were established on Lemon Creek Glacier, Juneau Ice Field, Alaska. Using the appropriate ice-rock density differential, cross-sectional shapes of the glacier are computed to fit observed variations in the Bouguer anomaly on traverses across the glacier. Results are presented on cross section diagrams and on an isopach map.

Introduction—For the past several years the American Geographical Society has sponsored a broad program of glaciological research on the Juneau Ice Field, southeastern Alaska. During the summer of 1956, as a part of this program, gravity measurements were made on Lemon Creek Glacier with the purpose of providing an estimate of glacier thickness. Lemon Creek Glacier adjoins the southern part of the Juneau Ice Field. It is seven kilometers long and averages about 1¼ km wide. The surface elevation varies from about 400 m at the terminus to about 1350 m at the upper end. Of this range a difference in altitude of 500 m occurs in the first two kilometers above the terminus.

Although the gravity method is inherently less accurate for glacier thickness studies than are seismic measurements, it has the advantage of simplicity and rapidity in the conduct of field operations. Where an estimate of glacier thickness is desired with the minimum of equipment and field work, the gravity method is recommended, and it is hoped that this report may serve as a guide to future work of this nature. The 182 gravity stations of the present survey, together with the necessary altimeter surveying from previously established benchmarks, required eight days field work of a three-man crew.

Field procedure—The instrument used for the gravity measurements was a Worden Geodetic Gravity Meter no. 10. This instrument had been used extensively by G. P. Woollard of the University of Wisconsin for intercontinental gravity measurements and had been calibrated against accurate gravity pendulum stations over a wide range of latitude. The calibration constant is therefore well known.

A small airplane with retractable skis was chartered to make a looped gravity tie over a short time interval between the main gravity base on the glacier and a gravity base in Juneau. Since the Juneau base is a part of the International Gravity Network, the observed gravity values are on an absolute basis.

The stations were located on the glacier by running line-of-sight traverses between cairns on the rock ridges enclosing the glacier. Distances between stations on any one traverse were chained. Locations were then easily plotted on a base map drawn from a control survey and aerial photographs of the previous summer. The locations of the most important traverses are shown on the aerial photo (Fig. 1).

The elevations of the cairns on opposite ends of a traverse were known from an accurate theodolite control survey. For the four principal traverses additional control points were established on the glacier by leveling. Between these benchmarks, elevation control for the gravity work was provided by altimetry. Two altimeters were read at each station and the average value adopted. The maximum difference in altimeter elevations, after correction for barometric fluctuation, was four meters; usually this difference was only one or two meters, and often the altimeter values agreed. For the most part, the elevations are probably accurate to two meters.

Reduction of the Observations—The time interval between field observation and depth determination places the gravity method at a disadvantage compared with seismic measurements. In seismic work a rough depth may be determined in the field immediately knowing the velocity of sound in ice and the travel time of a reflection as measured from the seismic record. In gravity work the final answer is available only after a certain amount of reduction in the office.

The observed (that is, measured) values of gravity reflect, in addition to the thickness of the glacier ice, effects of latitude, elevation, adjacent terrain, and geology. To eliminate certain of these effects it is customary to express the results of a

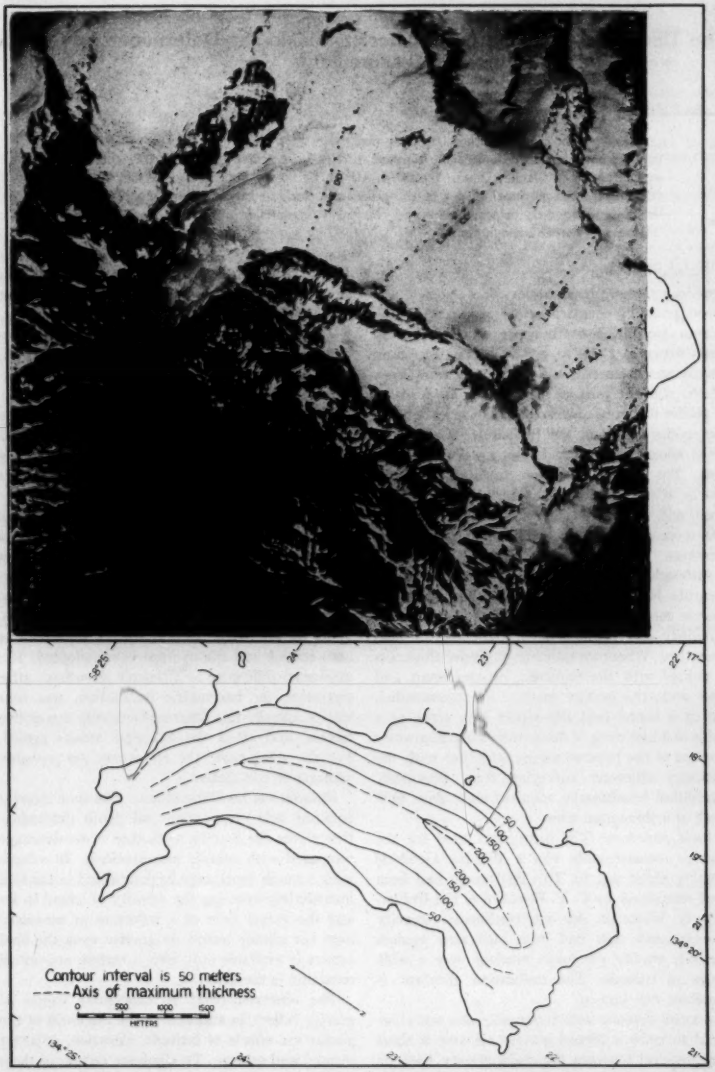

FIG. 1 – Aerial view of Lemon Creek Glacier showing the locations of the principal gravity traverses (U. S. Navy Photograph SEA 67(013), July 5, 1948; isopach sketch map, below

gravity survey in terms of anomalies in preference to using the observed values directly. The Bouguer anomaly is equal to observed gravity less theoretical gravity, or observed gravity minus (theoretical sea-level gravity minus free-air correction plus non-topographical Bouguer correction minus terrain correction). Theoretical sea-level gravity is obtained from the International Gravity Formula adopted by international agreement in 1930,

$$\gamma 0 = 978.0490\ (1 + 0.0052884 \sin^2 \phi - 0.0000059 \sin^2 2\phi) \text{gal}$$

where ϕ is latitude. The free-air correction reduces the theoretical sea-level value by an amount proportional to the elevation of the station above sea level; this correction equals 0.3086 mgal/meter. The non-topographical Bouguer correction allows for the attraction of the rock material between sea level and the point of observation, assuming that this material extends as a uniform infinite slab in all directions around the station; this correction equals 0.04185 ρ mgal/meter where ρ is the density of the rock. The country rock in the vicinity of Lemon Creek Glacier is a diorite, to some degree metamorphosed. From rock samples collected around the circumference of the glacier, a mean density of 2.76 was determined in the laboratory. This value is within the range cited by Daly for diorites [*Berman*, *Daly*, and *Spicer*, 1942, p. 14] and is adopted for the present work.

The terrain correction allows for the departure of topography from the level slab assumed in making the Bouguer correction. This correction was made from diagrams of the terrain effect for two-dimensional features which extend to infinity in the third direction [*Hubbert*, 1948b]. A terrain correction computed in this manner is admittedly not complete. It allows only for the ridges immediately bounding the glacier and does not account for the more distant topographical features. A complete terrain correction would require an accurate topographic map of the surrounding area, and this is not available for the Juneau Ice Field. However, the boundary ridges are the most important features to be accounted for; the more distant mountains and valleys will have an effect which is smaller and nearly equal for the adjacent stations of any one traverse.

(As this report was being written a paper appeared discussing gravity measurements on the Austerdalsbreen of southwest Norway [*Bull* and *Hardy*, 1956]. In their investigations the terrain effect was obtained by running a traverse across the valley below the terminus of the glacier. The anomalies, uncorrected for terrain, of this traverse were compared with the anomalies, also uncorrected for terrain, on a traverse across the glacier and the difference attributed to the low-density ice. This method of eliminating the terrain effect is perhaps less direct than the method employed on the present study. In any event, their method is inapplicable to Lemon Creek Glacier because the valley below its terminus strikes at right angles to the ice-filled valley, and the two portions of the valley are not at all similar. The Austerdalsbreen and Lemon Creek Glacier differ as regards the extent to which they fill their valleys. The Austerdalsbreen has steep valley walls rising high above the glacier, whereas Lemon Creek nearly fills its valley. The direct computation of the terrain effect is therefore easier to make and gives a value of greater certainty for Lemon Creek Glacier.)

Figure 2 presents the Bouguer anomalies computed in the above manner for several of the traverses. The end stations of each traverse are located on rock (ice thickness zero). The slope of the dashed line connecting the end stations represents a regional trend unrelated to the ice thickness. This trend is caused by regional changes in geology and in the present case probably reflects the decrease in Bouguer anomaly as one passes from an ocean toward the interior of a continent, an effect well known to students of isostacy.

The first rough determination of ice thickness is made from the Bouguer anomaly curve by applying the infinite slab Bouguer correction. This correction states that 78.4 ft of material with a density differential of 1.0 will produce an anomaly of one mgal, and assumes that the thickness of ice is the same in all directions about the point of computation. In the present survey the density differential is 2.76 (rock) minus 0.90 (ice) equals 1.86, or 12.85 meters of ice per mgal.

With an appropriate glacier cross section determined in this manner, it is possible to apply more refined methods to eliminate the assumption of infinite extent inherent in the Bouguer correction. A line integral method for calculating the gravity effect for bodies of arbitrary cross section, but infinite extent in the third dimension [*Hubbert*, 1948a], was used to obtain a cross section which approximately fits the Bouguer anomaly curve. The ice thickness calculated by this method is somewhat greater than that calculated from the Bouguer correction because when the horizontal extent of the ice is restricted, it must reach to greater depths to produce the same anomaly.

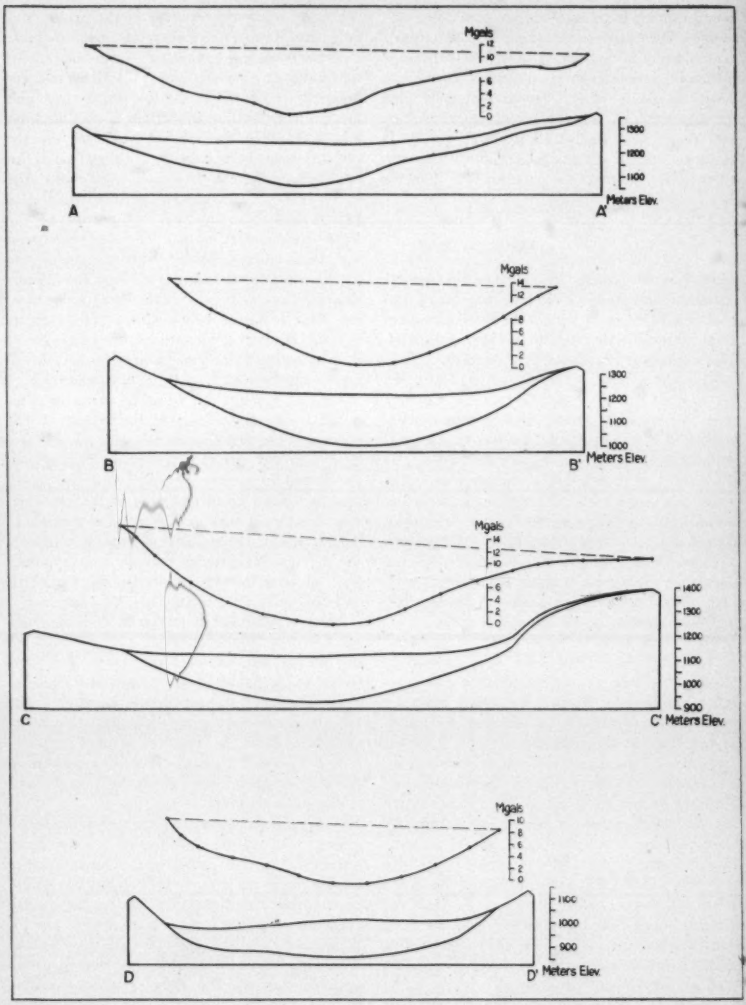

FIG. 2 – Bouguer anomalies and cross sections determined for Lemon Creek Glacier; vertical and horizontal linear scales are equal

Conclusions—The cross sections obtained as described above are given in Figure 2. The lower part of Figure 1 is an isopach map of the glacier compiled from the seven transverse traverses and the one long longitudinal traverse constituting the survey. The maximum ice thickness occurs in the upper central reaches of the glacier. The average longitudinal slope of the ice surface from the BB′ profile and a CD profile (intermediate between profiles CC′ and DD′) is 3.5° and from there to the icefall, 6.3°; the slope of the underlying rock surface over these regions is 2.4° and 4.6°, respectively.

Acknowledgments—The authors are indebted to G. P. Woollard of the University of Wisconsin for the loan of the gravity meter used in the survey. They also wish to express their thanks to the colleagues who assisted with the field work: M. W. Hane, Department of Physics, University of Washington, and W. E. Long, Department of Geology, University of Nevada. To C. J. Heusser, Project Officer for the Juneau Ice Field Research Project, and W. O. Field, Head of the Department of Exploration and Field Research for the American Geographical Society, the authors are grateful for assistance in the preparation of the paper and for permission to publish. The Juneau Ice Field Research Project is sponsored by the American Geographical Society under contract with the Office of Naval Research.

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The 'Boundary' of the Earth's Inner Core*

B. GUTENBERG

Abstract—Longitudinal waves PKIKP with periods of about one second which have passed through the inner core frequently arrive earlier than the corresponding waves with periods of several seconds. At epicentral distances between about 120° and 135° the difference in arrival between the first short-period waves and the long-period main impulse may reach nearly 20 sec. If this difference is a consequence of dispersion in a transition zone between the outer and inner core, the calculated 'radius' of the inner core is greater for short-period than for long-period waves. According to theoretical and laboratory research by Kuhn and Vielhauer such phenomena are to be expected if the transition from the outer to the inner core corresponds to a relatively rapid but continuous increase in viscosity without change in material. On the other hand, findings from all sources agree with the hypothesis that the boundary between mantle and core separates solid material (rock) in the mantle from a different liquid material (mainly iron) in the core.

Introduction—On the basis of various lines of research there is little doubt that the boundary between the mantle and the core of the earth corresponds to the transition from solid to liquid material. *Kuhn* and *Vielhauer* [1953] investigated the question, if this may correspond to a decrease in viscosity without change in material. They studied theoretically as well as by laboratory experiments the behavior of elastic waves in viscous media. They concluded that short- and long-period longitudinal waves crossing a boundary between the solid phase of one material and the liquid phase of a different material should arrive simultaneously at a given point. However, if they have passed through a zone of rapid transition from one state to another of the same material, travel times to a given point should depend on the period T. Kuhn and Vielhauer also found that in material of relatively small viscosity the bulk modulus should be a function of T.

The boundary between mantle and core—Waves reflected in the mantle at the core boundary with wave lengths of only 20 km or even less are observed frequently, and PKKP waves reflected inside the core at the boundary have occasionally lengths as short as ten kilometers. These results indicate a sharp boundary; travel times of these reflected waves as well as of various types of refracted waves traversing the outer portion of the core lead to the same value for the radius of the core within the limits of error of roughly ten kilometers regardless of the wave length. Moreover, thousands of pairs of records written by short- and long-period instruments show the same time of beginning for waves through the mantle. Since the core is liquid, the results of Kuhn and Vielhauer indicate that its boundary separates two different materials. Combination of all available data leads to the conclusion that near the core boundary the mantle consists of a solid material, the core of a different material of much lower viscosity.

The 'radius' of the inner core—The interpretation of travel times of waves through the inner core is less certain. *Gutenberg* and *Richter* [1934, p. 90] have pointed out that longitudinal waves through the core arriving at distances of less than about 140° (indicated here by the symbol P″) consists of a number of wave onsets culminating in a rather strong impulse about ¼ minute after the emergent first arrival of the phase. They also found that the corresponding travel time curves remain separate as far as they can be observed, and that the early P″ waves usually have relative short periods (T roughly one second); in the later waves of P″ longer waves ($T \geq 3$ sec) prevail.

Denson [1952, p. 133] concluded that the short-period and the long-period waves presumably "leave the source as one wave or as one composite energy spectrum distribution." His results show [*Denson*, 1952, Fig. 3, p. 123] that at epicentral distances up to about 145° short-period waves prevail by far in the early arrivals of P″ while the main onset and later portions of the P″ group include more long-period waves.

The fact that short-period P″ waves occasionally arrive 'too early' has been confirmed repeatedly. For example, in the *Preliminary Seismological Bulletin* for Uppsala and Kiruna, M. Båth points

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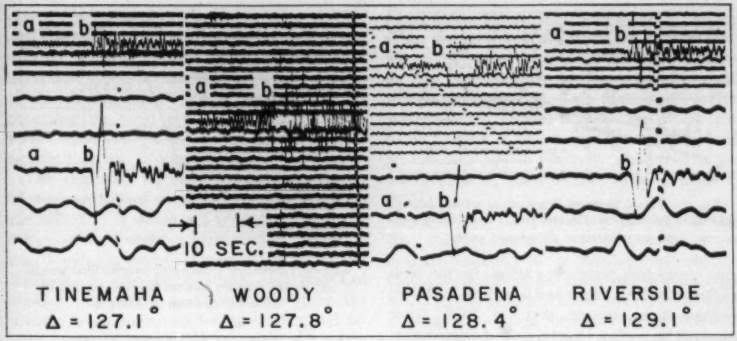

FIG. 1 – Portions of seismograms of earthquake, April 16, 1957, 4h GCT; distances are calculated from the U. S. Coast and Geodetic Survey epicenter, 4½° S, 107½° E; focal depth 600 km; on top records of short-period, below of long-period Benioff seismographs; (a) short-period, (b) long-period P″ waves.

out that in the earthquake of August 9, 1956, 23h, epicenter near Samoa, "the small-amplitude phase (PKP), arriving 12–13 sec earlier than the computed arrival of PKP is noteworthy." The epicentral distances are approximately 126° for Kiruna and 134° for Uppsala. The periods of PKP (P″ in our notation) are about one second. Such early arrivals of P″ are definitely not produced by small foreshocks and are not observed for P at short epicentral distances.

Excellent illustrations for the dispersion of P″ are furnished by records of the earthquake on April 16, 1957 at 4h 04m 04s GCT; according to the U. S. Coast and Geodetic Survey its epicenter was at 4½° S, 107½° E; its focal depth was about 600 km. Examples of records are reproduced in Figure 1. At distances between 120° and 135° travel times of the main P″ phase (marked b in Fig. 1; period about 3 sec) agree within 2 or 3 sec with those calculated on the basis of standard travel time curves for P″. The first short-period waves of P″ (marked by a in Fig. 1) arrived about 16 seconds 'too early.' They have not been reported for Shasta (122.6°) and are very doubtful at Berkeley (123.9°) but have been clearly recorded at Lick (124.5°). The most distant stations where they have been observed seem to be Boulder, Colorado (133.9°), and Tucson (134.7°) where small waves (T = ½ sec) start 16 sec and one wave (T = 2 sec) about 11 sec preceding the main impulse (T = 4 sec); at distances over 139° (including Ottawa, Lubbock, Harvard, all between 139° and 142°) the early P″ waves have not been reported in the preliminary list of data of the U. S. Coast and Geodetic Survey. At Palisades (143.6°) the short-period Benioff vertical shows no trace of a wave preceding a sharp large impulse arriving at the calculated time.

For an explanation of the fact that short-period P″ waves precede waves having longer periods it may be assumed that near the 'boundary' between the outer and inner core the waves undergo dispersion in crossing a transition zone where the viscosity increases rapidly downward with consequences outlined in principle by *Kuhn* and *Vielhauer* [1953].

For the following calculations it is assumed that the earliest travel-time curve in Figure 2, based on observations of *Denson* [1952], corresponds to short-period PKIKP waves; adopted travel times are listed in Table 1. Such travel time for short-period P″ waves should be included

TABLE 1 – *Assumed travel times t of short-period P″ waves*

Δ	t	Δ	t
°	min sec	°	min sec
124	18 50	144	19 32
126	18 55	146	19 36
128	19 00	148	19 40
130	19 04	150	19 44
132	19 08	152	19 47
134	19 12	154	19 50
136	19 16	156	19 53
138	19 20	158	19 57
140	19 24	160	20 01
142	19 28		

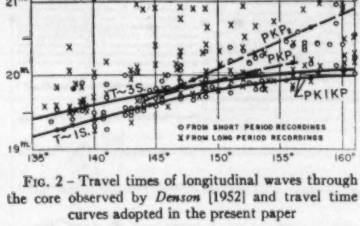

FIG. 2 – Travel times of longitudinal waves through the core observed by *Denson* [1952] and travel time curves adopted in the present paper

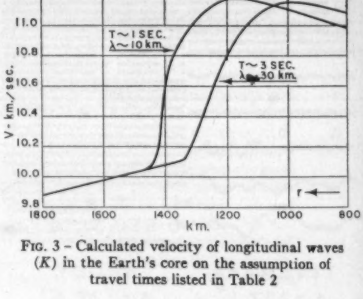

FIG. 3 – Calculated velocity of longitudinal waves (K) in the Earth's core on the assumption of travel times listed in Table 2

now in standard travel-time tables. On the basis of *Denson's* [1952, Fig. 8 and 9, and pp. 127–131] findings it is assumed that the PKP_1 curve (through the outer core only) ends at an epicentral distance of $\Delta = 157°$.

Except for travel times corresponding to the end of the curve for PKP_1 the adopted times for PKP are the same as those assumed by *Gutenberg* [1951] on the basis of older observations; they agree with the travel-time curve for K (inside the core) calculated from observed travel times of PKKP and SKS. While the complicated travel-time curves (Fig. 2) do not permit accurate determination of the times for the PKP branches, there is no doubt about their focal point at a distance near 144°, especially for long-period waves [*Denson*, 1952, p. 123; *Gutenberg*, 1951, p. 383]; according to *Denson* [1952] the focal point is less clearly observed for short-period waves.

Finally, it was assumed that P″ begins at $\Delta = 124°$. So-called P″ waves arriving at $\Delta < 124°$ may be reflected at the inner core; they are small and have short periods.

TABLE 2 – *Assumed travel times t of short-period waves starting and ending at the boundary between mantle and core*

Δ	t	Δ	t
°	min sec	°	min sec
10	1 15	120	10 40
20	2 28	130	11 06
30	3 41	120	10 41
40	4 51	110	10 16
50	5 52	100	9 52
60	6 46	110	10 14
70	7 33	120	10 33
80	8 18	130	10 50
90	9 00	140	11 06
100	9 40	150	11 21
110	10 12		

By use of the method of *Wadati* and *Masuda* [1934], travel times for K, longitudinal waves starting and ending at the boundary of the core, have been calculated (Table 2). The corresponding wave velocities have been found by use of the Wiechert-Herglotz method as extended by *Slichter* [1932].

In Figure 3, the resulting wave velocities for short-period waves (corresponding to the earliest curve in Fig. 2) have been plotted as function of depth together with the earlier results [*Gutenberg*, 1951] corresponding to the main travel-time curve for waves with periods of several seconds. Details are not reliable. For example, the slight decrease in velocity with depth inside the inner core may result from the difficulty in establishing accurate travel times for the various branches of P′, especially from incorrect assumptions for the end of PKP, and for the times corresponding to the reversed segment (not plotted in Fig. 2) between the end of the curve for PKP_1 (at 157°) and the beginning of the curve for PKIKP (P″ at 124°). However, a slight decrease in wave velocity towards the center of the Earth has been found on many assumptions, and the relatively small amplitudes of PKIKP at large distances, especially of its short-period beginning, could be at least partly the result of a decrease in wave velocity with depth.

The calculations of the depths at which the velocity increase for short- and long-period waves begins (Fig. 3) depend appreciably on the assumed distances at which PKP_1 ends. These distances can not be found accurately for short- or long-period waves from travel time observations (Fig. 2); however, the assumptions concerning travel-time curves for the various branches are limited by the requirement that the apparent wave

velocity increases with decreasing angle of incidence. Thus, in Fig. 3 the depths at which the velocity begins to increase rapidly are somewhat uncertain. However, the relatively early arrival of the short-period P″ waves requires that, approaching the inner core, the velocity of short waves increases earlier and, especially, more rapidly than that of longer waves.

The dispersion of the P″ waves corresponds to the conclusions of Kuhn and Vielhauer for the transition of waves in a given material across a zone of rapid change in viscosity. In comparing Fig. 3 with the conditions expected by Kuhn and Vielhauer it must be considered that they had applied their results to the transition from the mantle to the outer core for which they had assumed a rapid decrease in viscosity with depth while in the present paper an increase in viscosity with depth from the outer core to the inner core is postulated.

The new results (especially Fig. 3) improve the agreement between calculated and observed travel times of waves through the core. However, there is no proof that it is the only possible solution. It is based on the assumption that the waves are propagated along rays following Snell's law. It is frequently overlooked that the usual wave theory is only a first approximation which fails for example when the velocity gradient changes appreciably over a distance of the order of a wave length or when the energy gradient along the wave front becomes comparable to that in the direction of the ray; such conditions must be expected, if near the boundary of the inner core the velocity increases rapidly with depth. F. Press has pointed out that frequency selective diffraction has been observed under similar conditions near the ocean bottom. *Press* and *Dobrin* [1956] have shown how a velocity change may result in high-pass filtering of seismic waves. Thus diffraction, possibly in combination with the processes described by Kuhn and Vielhauer, may be involved. However, this would also require a rapid increase of velocity in a transition zone between the outer and the inner core.

A further study of all problems involved is desirable. The failure to find a gradual increase in wave periods from the beginning of the short-period P″ waves to the long-period impulse of P″ may result from the predominance of certain periods in earthquake waves. Indications of relatively small dispersion throughout the outer core [*Denson*, 1952] should be investigated as well as the effect of ellipticity of the core on the observed travel times. The recorded long-period P″ waves of the shock on April 16, 1957 (Fig. 1) show that the main P″ phase consisted of practically a single wavelet. The relation of the relatively great number of short-period waves to this single longer wave requires further research concerning the whole problem of seismogram spectra. Effects of ground may play a relatively great role in the multiplicity of short-period waves [*Gutenberg*, 1957].

Conclusion—The present investigation indicates that there is dispersion for longitudinal waves near the 'boundary' of the inner core and that the apparent 'radius' of the inner core is greater for waves having periods of about one second (lengths of about 10 km) than for waves having periods of about three seconds. All data now available support the conclusion that the surface of the outer core is a distinct boundary between solid rock in the mantle and liquid material of a different type (probably mainly iron) in the core while between the outer and the inner core there is no sudden change in material, but a transition from the 'liquid' state to one with much higher viscosity.

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A Method to Determine the Isotopic Ratio of Thorium^{232} to Thorium^{230} in Minerals

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Abstract—The isotopic ratio of Th^{232} to Th^{230} was determined in uranium minerals. The thorium was separated from the mineral. The amount of Th^{232} was determined by activation analysis and that of Th^{230} by counting its α particles. The ratio of the two isotopes was calculated by comparing the β and α activity of the two thorium isotopes in the sample to those of a standard of known Th^{232} to Th^{230} ratio.

Introduction—An ever increasing interest prevails in the geological distribution of thorium, and in the thorium content of uranium minerals. If the thorium concentration is low, the conventional analytical methods of analysis are not sensitive enough to determine less than 0.01 pct. The lower limit of the thoron streaming method is about 10^{-6} g per kg sample. Counting α tracks in nuclear emulsions is very time consuming. The problem becomes more difficult when very small amounts of thorium are to be analyzed in the presence of large amounts of uranium. This is often true in pitchblende and uraninites. The isotope dilution method [*Tilton* and others, 1954] was applied recently to the determination of microgram and submicrogram amounts of thorium in minerals and rocks. Much useful information can be expected from the application of this method.

This paper does not attempt to describe the determination of absolute amounts of thorium, but rather its isotope ratio. This ratio is also indicative of that of Th^{232} to U^{238}. Thorium^{230} (commonly called ionium) is a daughter of uranium; its ratio to uranium can be calculated from the familiar equations of radioactive equilibrium although the calculation of Th^{232} to U^{238} ratio from that of Th^{232} to Th^{230} is valid only if Th^{230} is not removed from the mineral during the last million years.

Method—The thorium isotopes are first separated from other elements of the mineral. The sample is then subjected to the bombardment of slow neutrons. The β activity of the Th^{233} produced from Th^{232} by the (n,γ) reaction, is determined as well as the α activity of the naturally radioactive Th^{230}. A standard with known Th^{232} to Th^{230} ratio is exposed to the same neutron flux under exactly the same conditions as the unknown sample. From the α to β ratio of the standard and that of the sample, the Th^{232} to Th^{230} ratio of the sample can be calculated. The obvious advantage of this method is that the ratio of the two isotopes remains constant in any aliquot of the dissolved mineral and for this reason losses in chemical separation are not involved in the calculations.

Chemical Separation—A procedure of *Peppard* and others [1953] was followed with some modifications. The β activity of Th^{234} ($t_{\frac{1}{2}}$ = 24.1 days) was used as a tracer to follow the yield losses in separation. The α activity of U^{232} ($t_{\frac{1}{2}} = 1.65 \times 10^5$ yr) was used as a tracer for U^{238} (see Fig. 1).

The element that interferes most in the determination of Th^{232} by activation analysis is uranium. Uranium^{238} bombarded with slow neutrons yields U^{239}. This isotope has approximately the same half life, the same beta energy as Th^{233}, and the same activation cross section for U^{238} as for Th^{232}. The only method of identification is by means of its gamma radiation of 0.076 Mev. Thorium^{233} does not emit gamma radiation. Since the samples must be completely free from uranium, this was accomplished by the final steps of purification. The sample in a solution of 8 M HCl was applied to an ion exchange column of Dowex-1 anion exchanger [*Kraus* and others, 1955]. Uranium was absorbed on the resin whereas thorium was collected in the 8 M HCl eluant. It was converted into nitrate (0.1 N HNO_3) and extracted into a benzene solution of 0.1 M thenoyltrifluoroacetone (TTA) and stripped with one N HNO_3 solution [*Hageman*, 1950]. The standard and unknown samples were then both evaporated in a small tube of transparent fused quartz. The samples were then exposed to the slow-neutron flux in the graphite reactor of the Argonne National Laboratory, or that of the Oak Ridge National Laboratory for 45 min. The sample and the standard were then taken up with a few drops of nitric acid and deposited on a platinum plate. All organic residues were burned off. The samples had no visible deposits and were well suited for α counting.

Contamination—Contaminations can originate from reagents, glass containers, and air.

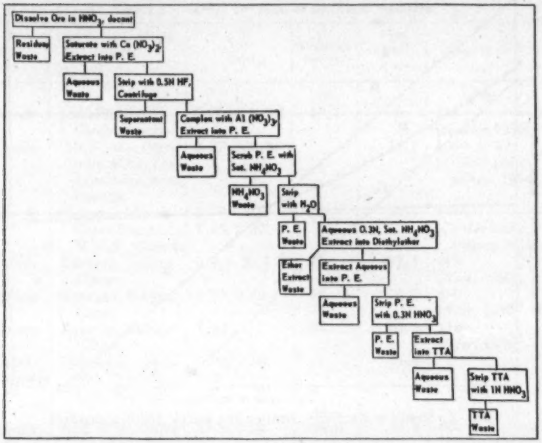

FIG. 1 – Flow sheet of chemical analysis

Reagents—The reagents were purified by several processes. Dibutoxytetraglycol (PE) was scrubbed successively with HF, dilute HNO_3, and triple distilled water. The ethyl ether was scrubbed with 0.3 N HNO_3 saturated with recrystallized NH_4NO_3. Water was distilled three times and the HNO_3 and HCl twice in borosilicate glass. Thenoyltrifluoroacetone was scrubbed with 1 N HNO_3. To test the purity of the water and acids, 100 ml of each was evaporated and exposed to the slow neutron flux. They were found to be free from any impurity, except for a very small amount of silicon ($t_{\frac{1}{2}}$ = 180 min).

Glass containers—Borosilicate glassware was cleaned by boiling with 8 N HNO_3 repeatedly, thoroughly rinsed with tridistilled water and kept sealed with semiadhesive 'parafilm' while not in use.

Airborne contamination—There is no way to check airborne contamination at the required sensitivity level.

Measurement—The following reactions take place when the sample and the standard are exposed to slow neutron flux.

$$Th^{232}\ (n, \gamma)\ Th^{233} \xrightarrow[23.3\ \text{min}]{\beta} Pa^{233} \xrightarrow[27.4\ \text{days}]{\beta}$$

$$U^{233} \xrightarrow[1.65 \times 10^5\ \text{yr}]{\alpha}$$

$$Th^{230}\ (n, \gamma)\ Th^{231} \xrightarrow[25.6\ \text{hr}]{\beta} Pa^{231} \xrightarrow[3.4 \times 10^4\text{yr}]{\beta}$$

Thorium^{234} ($t_{\frac{1}{2}}$ = 24 days) might also be present from the uranium chain. It decays to the β emitter Pa^{234} (2.3 MeV) which is in secular equilibrium with it. This activity was subtracted from that of Th^{233}. The weak β radiation of Th^{234} can be corrected. However in most of the samples Th^{234} decayed to a negligible amount at the time of analysis.

Beta counting—Beta counting was usually carried out in a methane flow end-window type proportional counter or in a Geiger-Muller counter. The soft β radiation from Th^{231} and Th^{234} was absorbed in an aluminum filter of 80 to 100 mg/cm^2. The beta activity of the sample and of that of the standard was counted for several hours.

Gamma counting—Gamma counting was carried out with a scintillation counter having a $1\frac{1}{2} \times 1$ inch Tl activated NaI crystal, $A - 1$ linear amplifier, and single-channel pulse height analyzer. A 0.755 g beryllium absorber was placed between the crystal and the sample. The scintillation counter was standardized with a Cs^{137} (0.66 MeV γ energy) sample or Pm^{145} sample (0.068–0.071 MeV γ rays, personal communication of B. H. Ketelle). Some of the samples were scanned with a sixty-channel analyzer for impurities. The amount of activity was negligible for the range of a few KeV to a few

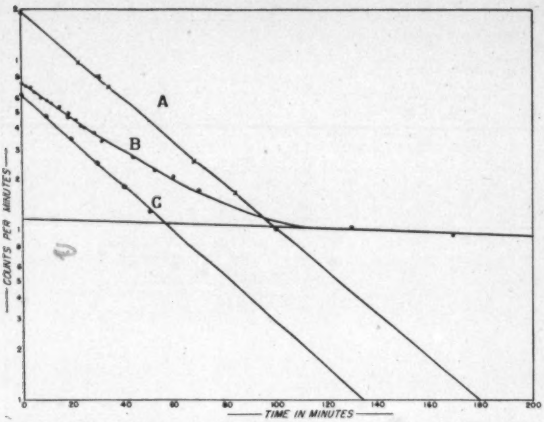

FIG. 2 – Result of β activity counting in a sample and in a standard

MeV. To determine the limit of detection of uranium, isotopically pure U^{238} was exposed to a slow neutron flux and the γ radiation (0.076 MeV) measured in the scintillation spectrometer. The lower limit of detection was determined as being about 0.001 micrograms.

Alpha counting—Alpha counting was carried out with a system designed at the Oak Ridge Institute of Nuclear Studies. It consists of an argon filled ionization chamber in conjunction with a high gain amplifier and scaler. The background of the ionization chamber was around one count per min.

Standard—The Th^{232} to Th^{230} ratio of the standard was 5.98. This was determined by mass spectrometer.

Errors—The losses in separation of thorium from mineral solutions affect both thorium isotopes in the same way and do not affect their ratio. There are two serious sources of error, (1) incomplete separation of uranium as mentioned previously, and (2) contamination. To assess the amount of contamination derived from different sources, duplicate determinations were carried out on the same mineral, varying the weights of the mineral sample but using the same amounts of reagents. Corrections caused by the β activity of the reagents used were carried out by subtracting it, together with the β activity of Pa^{234} from the β activity of Th^{232} (Fig. 2).

Limits of detection—From the equation for radioactivation, one can calculate the lowest limit of thorium that can be detected.

$$g = \frac{(\mathrm{d/sec}) \times A}{6.02 \times 10^{23} \times \sigma \times f \times S}$$

g gram of thorium (Th^{232}) of the target
A atomic weight of Th^{232}
6.02×10^{23} Avogadro's number
σ cross section for Th^{232} (n, γ) reaction
f number of neutrons per sec per cm^2
S $1 - e^{-\lambda t}$ saturation factor, where λ is the decay constant of Th^{233} and t the time of exposure to the neutron flux.

If one assumes 20 distintegrations per second as a practical lower limit for beta activity of Th^{233}, the activity can be conveniently counted. By inserting this limit, the flux of the reactor, the cross section of Th^{232}, and the saturation factor, the following calculation gives the weight of Th^{232} which can be detected by this method.

$$g = \frac{20 \times 232}{6.02 \times 10^{23} \times 7 \times 10^{-24} \times 5 \times 10^{11} \times 0.733}$$

$$= 1.64 \times 10^{-9} \text{ g of thorium}$$

TABLE 1 – *Calculation of Th^{232}/Th^{230} from the data of a typical experiment*

Item	Ratio
β/α standard	3.02
β/α sample	0.72
$\frac{\beta/\alpha \text{ standard}}{\beta/\alpha \text{ sample}}$	0.238
Th^{232}/Th^{230} standard	5.98
Th^{232}/Th^{230} sample	$0.238 \times 5.98 = 1.42$

TABLE 2 – Th^{232}/Th^{230} *ratio in uranium minerals*

Sample	Mineral	Source	$\frac{Th^{232}}{Th^{230}}$	Uranium content	$\frac{Th^{232}}{U^{238}} \times 10^4$	Age × 10^6	Remarks
				pct		year	
1	Pitchblende	Joachimsthal, Czechoslovakia	0.00 ± 0.001	45.7	0	215 [*Marble*, 1936]	....
2	Pitchblende	Cinch Lake, Uraninite Mine, Lake Athabaska, Sask. Canada	0.77 ± 0.01	....	14.1	1030 ± 50[a] [*Collins* and others, 1954]	....
3	Pitchblende	Eldorado Mines, Great Bear Lake, N.W.T., Canada	1.55, 1.66 1.35, 1.37	52.0	29.3 24.9	1410 [*Collins* and others, 1954]	Split sample Diff. sample
4	Pitchblende	Katanga, Belgian Congo	9.9, 9.50, 9.72	75	177.5	610 [*Nier*, 1939]	....
5	Pitchblende	Katanga, Belgian Congo	9.27, 9.40	75	170.7	610 [*Nier*, 1939]	....
6	Pitchblende	Katanga, Belgian Congo	7.60	75	139.0	610 [*Nier*, 1939]	....
7	Presumably pitchblende	Unknown, probably Great Bear Lake Region	2.86, 2.88 3.0	....	51.4	....	Split sample diff. piece same mineral
8	Pitchblende	Kirk Mine, Gilpin County, Colorado	27.9, 26.2	39.0	47.4	60 [*Kulp*, 1954]	Indepemdent chemistry
9	Uraninite	Wilberforce, Canada	53	60.0	969.4	1040 [*Kulp*, 1954]	....
10	Carnotite	Colo-Utah region	28.0	....	512.0	....	....
11	Samarskite	Mozambique, East Africa	1300	6.2	23,790	....	....

[a] Personal communication from R. M. Farquhar.

Sources of material—The following additional information is given concerning the samples listed in Table 2.

(1) Pitchblende, Joachimsthal, Czechoslovakia. Ten grams were received from the late J. P. Marble. The mineral did not show any signs of weathering. The accompanying letter stated the uranium content as 45.7 pct and that no thorium was detectable by the peroxynitrate method.

(2) Pitchblende, Cinch Lake Uranium Mine, Lake Athabaska, Sask., Canada. Received through the courtesy of R. M. Farquhar. Well-preserved sample.

(3) Pitchblende, Eldorado Mines, Great Bear Lake, Canada. Received from the late H. V. Ellsworth. No alteration visible [*Ellsworth*, 1932].

(4) Pitchblende, Katanga, Belgian Congo. Handpicked sample from Katanga Mine through courtesy of John W. Ruch, Feed Material Division, Atomic Energy Commission, Oak Ridge, Tennessee.

(5 & 6) Pitchblende, Katanga, Belgian Congo. Obtained through the Division of Raw Material, Atomic Energy Commission, New York.

(7) Pitchblende, probably Great Bear Lake Region, Canada, from unknown source.

(8) Pitchblende, Kirk Mine, Gilpin County, Colorado. Obtained through the Division of Raw Material, Atomic Energy Commission, New York.

(9) Uraninite, Wilberforce Pit 4, Canada. From the late H. V. Ellsworth, uranium content reported as 53.52 pct and thorium 7.93 pct [*Ellsworth*, 1932].

(10) Carnotite, Colorado Plateau, Utah. Streaks of yellow uranium oxide in a piece of gray mineral. Courtesy of John W. Ruch.

(11) Samarskite, Mozambique, Africa. Obtained through Division of Raw Materials, Atomic Energy Division, New York.

For a typical experiment using a sample of mineral weighing ten grams and containing 52 pct uranium, the weight of Th^{232} detected corresponds to four parts of Th^{232} per 1×10^4 part of U. Consequently, one could reduce the amount of sample material required considerably to retain adequate sensitivity.

Results from a typical experiment are summarized in Table 1. The beta measurements are obtained from the curves as shown in Figure 2. In this figure, Curve A shows the decay of Th^{231} of the standard and B that of the sample. When Curve B is corrected for the activity of Pa^{234} and for the contaminants from the reagents, Curve C

results. In this experiment the beta-ray counting rate for the standard was 19,800 counts per minute, while the sample gave a beta counting rate of 6400. Corresponding alpha measurements gave a counting rate of 6550 counts per minute for the standard and 8870 counts per minute for the sample. From Table 1 it is seen that the Th^{232} to Th^{230} ratio in this sample is 1.42.

The third column of Table 2 gives the experimentally determined Th^{232} to Th^{230} ratio. The uranium content of the mineral in the fourth column was either given to the author by the donor of the respective mineral or taken from the literature. This value is given to evaluate the concentration of thorium in the presence of very much larger amounts of uranium. The exact location of the mineral for Samples 4, 5, 6, and 11 is not known. Sample 1 is the only mineral in which no Th^{232} was found in the limit of sensitivity of the method. Other primary mineral samples 2 to 7, have low but detectable Th^{232} to Th^{230} ratios. Samples 10 and 11 show signs of alteration.

Discussion—One of the most interesting applications of the analysis of thorium, uranium, and lead in radioactive minerals is the determination of their isotopic ages from the Pb^{206}/U^{238}, Pb^{207}/U^{235} and Pb^{208}/Th^{232} ratios. All of the isotopic ages of radioactive minerals are more or less affected by the admixture of original common lead, defined by *Kovarik* [1931] as the Pb^{204}, Pb^{206}, Pb^{207}, and Pb^{208} present, which was precipitated with the uranium and thorium at the time of formation of the radioactive mineral. Original radiogenic lead is defined [*Stieff* and *Stern*, 1955] as the Pb^{206}, Pb^{207}, and Pb^{208} present which was precipitated with uranium and thorium at the formation of the radioactive mineral. Different methods have been suggested to correct for the amount of these lead contaminations. *Nier* [1939] in his fundamental paper, suggests that the Pb^{208}/Pb^{204} ratio of thorium-free minerals should be compared to that of uncontaminated lead and should be used as a correction. This method of correction should be applied with caution, unless sensitive methods show a low Th^{232} concentration so that the Pb^{208} in equilibrium with it does not introduce an appreciable error in the appraisal of the common lead of the mineral. In high grade pitchblende the small amounts of Th^{232} present, will not introduce significant errors if Pb^{208} is used as an indicator for the common lead content of the mineral.

An important factor for the validity of the determination of the Th^{232}/U^{238} ratio from that of Th^{232}/Th^{230} rests on the assumption that no Th^{230} was preferentially removed from the mineral. There is no easy way to evaluate to what extent Th^{230} is removed from the mineral, if at all, without the removal of equivalent amount of uranium in a certain mineral. There is, however, some indirect evidence. In minerals of low Pb^{206} to U^{238} and high Pb^{207} to Pb^{206} age, leaching or the removal of one of its precursors is indicated. Loss of radon was considered as the most important factor of the Pb^{206} deficiencies [*Wickman*, 1942; *Giletti* and *Kulp*, 1955; *Kulp*, 1954]. *Kuroda* [1955] demonstrated in his paper on the isotopic composition of radium in uranium minerals, that fractionation of intermediates did indeed occur. For pitchblende from Joachimsthal (Sample 1) and from Great Bear Lake (Sample 3) he found that equilibrium prevailed between Ra^{226} and U^{238} and, consequently, between Th^{230} and U^{238}. These conditions are very difficult to assess since they depend on the preservation of the mineral and its geological history.

Analyses of minerals for thorium with the present method will contribute to the clarification of these factors. With the method described in this paper, it was possible to determine the thorium concentration of a series of pitchblende for which no thorium concentration was known. In the world wide survey for thorium, this sensitive method may be helpful in the analyses of low grade thorium minerals.

Acknowledgments—The experiments described in this paper were started at the Chemistry Department of the Argonne National Laboratory and completed at the Oak Ridge Institute of Nuclear Studies. The author is indebted to W. M. Maning for suggesting the method, and to D. F. Peppard for supplying a Belgian Congo pitchblende concentrate and for his advice in the chemical separation. The help of B. H. Kettelle and A. R. Brosi, of the Oak Ridge National Laboratory, is gratefully acknowledged for making laboratory and counting facilities available for processing and counting the short half-life Th^{232} samples and of F. M. Porter for making the 60-channel analyzer available; of R. T. Overman for helpful discussions. E. K. Hyde kindly provided the Th^{232}/Th^{230} standard. This work was undertaken at the Oak Ridge Institute of Nuclear Studies under contract to Atomic Energy Commission.

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Discussion of "Properties of Shoaling Waves by Theory and Experiment"

PETER S. EAGLESON

[Trans., 37, 565–572, 1956]

R. L. Wiegel (University of California, Berkeley, California, received September 18, 1956)—Eagleson finds, as have other investigators, that Stokes' third approximation for wave celerity in water of finite depth does not agree with measured values in relatively shallow water: a divergence occurs. One of the difficulties is in connection with the series used to express the celerity, which is in terms of d/L (water depth divided by wave length) and H/L (wave height divided by wave length). The series does not converge rapidly for small values of d/L. The equation used by Eagleson is for a wave of small but finite steepness (H/L) and is due to *Wolf* [1944] who found certain errors in the original work of *Stokes* [1880 and *Struik* [1926].

$$C^2 = \frac{gL}{2\pi} \tan h \frac{2\pi d}{L} \left\{ 1 + \left(\frac{\pi H}{L}\right)^2 \left[\frac{2\left(\cos h \frac{4\pi d}{L}\right)^2 + 2\cos h \frac{4\pi d}{L} + 5}{8\left(\sin h \frac{2\pi d}{L}\right)^4} \right] \right\} \qquad (16)$$

The effect of d/L upon wave celerity as given by the above equation has been plotted by *Morison* [1951] as shown in Figure 6. It can be seen that the correction factor becomes exceedingly large with a decrease in d/L below 0.1; in fact, for finite values of H/L it grows without bounds as cosh $(4\pi d/L \to 1$, and sinh $(2\pi d/L) \to 0$ as $d/L \to 0$.

Wolf [1944] developed the equation for wave celerity in water of finite depth to the fifth approximation. For this case the relationships among wave celerity, wave length, wave height, and water depth were of such a nature that a solution for the wave celerity must be obtained by successive approximations.

Hunt [1953] has also pointed out the errors in the wave-celerity equations (for third approximations) of Stokes and Struik, and he points out that the equation of the type used herein is not applicable for large values of H/L.

Stokes [1880, p. 325] comments upon his series for small values of d/L as follows:

> "But with all due allowance to this consideration, it must be confessed that the approximation is slower in the case of finite depth. That it must be so is seen by considering the character of the developments, in the two cases, of the ordinate of the profile in a harmonic series in terms of the abscissa, of a quantity having the same period and the same mean value as the abscissa. The flowing outline of the profile in deep water lends itself readily to expansion in such a series. But the approximately isolated and widely separated elevations that represent the profile in very shallow water would require a comparatively large number of terms in their expression in harmonic series in order that the form should be represented with sufficient accuracy. In extreme cases the fact of the wave being in series at all has little to do with the character of the motion in the neighborhood of the elevations, where alone the motion is considerable, and it is not therefore to be wondered at if an analysis essentially involving the length of a wave should prove inconvenient."

An additional fact should be brought out. Waves in shoaling water decrease in length and increase in height (except for a small region of d/L), and therefore $H/2L$ increases while $(d/L)^2$ decreases. As *Stokes* [1880, p. 210] pointed out, it is necessary for $H/2L$ to be small in comparison with $(d/L)^2$ (that is, $L^3H/2d^3$ must be small) in order that his method of approximation may be legitimate. This has been discussed in detail by *Ursell*]1953] for the case where there is no reflection of energy from a sloping beach.

Recently a comparison has been made between cnoidal waves and Stokes' waves by *De* [1955]. It appears that cnoidal wave theory is better when considering waves in shallow water than is the theory of Stokes' waves. De extended both theories to the fifth order. He showed, by comparing certain features of the theories, that Stokes' theory (to the fifth order) should not be used for d/L less than about 0.125, the minimum value depending upon the value of H/L, with the greater the values of H/L, the greater is the value of d/L, at which Stokes' theory becomes unreliable.

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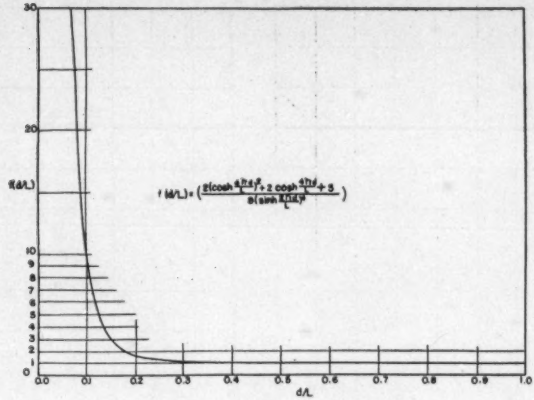

FIG. 6 – $f(d/L)$ versus d/L

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P. Danel (Societé Grenobloise d'Etudes et d'Applications Hydrauliques, Grenoble, France; received March 4, 1957)—Eagleson's interesting paper has the great merit of showing that certain simple theoretical formulas (such as Airy's), giving the wave celerity to the first approximation, and the energy-balance theory, giving wave height in terms of water depth, often provide a very close approximation to nature.

It is particularly worth noting that when the bottom is sloping, the formula giving the speed of propagation to the first approximation provides better results than the formula to the third approximation known as Stokes' equation (Eq. (6) of Eagleson).

However Stokes himself pointed out in his *Scientific Papers* that for this degree of approximation it is possible to define an infinite number of celerities depending upon the choice of reference axes. The reference axes that would seem most suitable for experiments like those carried out by Eagleson (in a flume closed at both ends) are those chosen such that the horizontal projection of the velocity of the center of gravity of the mass of fluid contained between two planes sufficiently far apart and normal to the direction of wave propagation has a temporal average of zero.

This particular celerity is not calculated in Stokes' works but it is given by *Biesel* [1951].

The difference between the celerity given by Stokes and that given by Biesel is

$$\sqrt{\frac{gL}{2\pi}\tan h\,\frac{2\pi h}{L}}\left(\frac{2\pi}{L}\right)^2 \left(\frac{1}{2\sin h^2\,\frac{2\pi h}{L}}+\frac{\cot h\,\frac{2\pi h}{L}}{2\pi\,\frac{h}{L}}\right)$$

We have calculated the theoretical celerity for the waves shown on Figure 1, using the data given on the figure. On the left side of Figure 7 we reproduce the comparison given by Eagleson between experimental celerity and the theoretical celerity given by (6), and on the right side we compare the experimental celerity with that given by Biesel, which we may call Stokes' theoretical modified celerity.

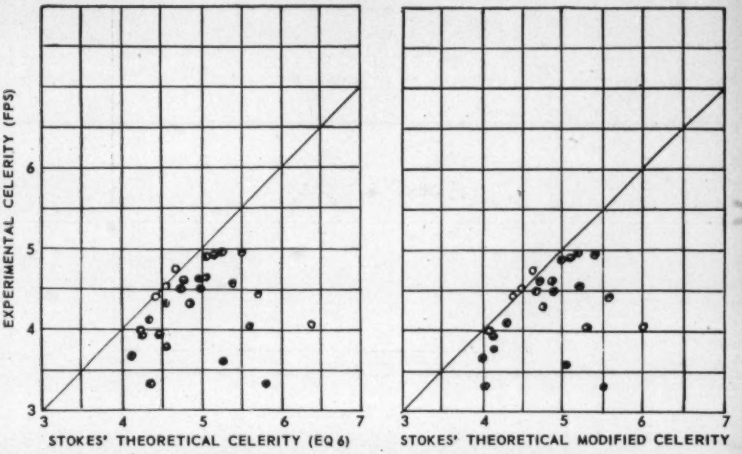

FIG. 7 – Comparison of theoretical and experimental celerities

We have made the comparison only for celerities below five feet per second. Above this value the two celerities differ by less than 0.04ft/sec. It can be seen that the modified Stokes celerity brings the theoretical and experimental results closer together without, however, reconciling them completely.

The Laboratoire Dauphinois d'Hydraulique has carried out a number of systematic experiments on the physical characteristics of waves in a constant depth of water. The experimental results were checked with theory to the first, second, and third approximations and the first approximation was often very close to the experimental results.

The more important part of these experiments and comparisons is summarised by *Suquet* and *Wallet* [1953].

We think it would be worth-while to give an outline here of the main results obtained concerning celerity. We should point out that celerity measurements can be made much more accurately when the bottom is flat than when it is sloping.

(1) Like Eagleson we found that the formula

$$C_1 = \sqrt{\frac{gL}{2\pi} \tan \mathrm{h} \frac{2\pi h}{L}}$$

which gives the celerity to the first approximation, furnishes very good results, especially for waves of small steepness and for high values of the ratio h/L.

Or, more precisely, when the steepness approaches zero the measured celerity is slightly less than the theoretical celerity given by the formula to the first approximation. The difference is about 0.5 pct.

This difference may be attributed to a number of factors that tend to slow the wave down, such as viscosity of the water, the fact that the waves are at an air-water interface and the density of air is not zero, elasticity of flume walls (steel plate) and compressibility of the water, and stratification of the water, the surface layers of which were heated by the lighting; little is known about this last factor.

(2) The celerity follows the formula to the third approximation very closely up to quite high steepness values, but even the first approximation is accurate to within ± one per cent as long as the steepness does not exceed six per cent. This is true even for values of h/L as small as 0.2.

(3) For steeper waves the points representing $(Cm - C_1)/C_1$ plotted against steepness (where Cm is the experimental celerity) lie very close to the group of theoretical curves of $(C_3 - C_1)/C_1$ against steepness (where C_3 is the theoretical celerity to the third approximation calculated with the modified Stokes formula). The deviations are only of the order of one per cent.

Waves of steepness up to 11 pct were studied.

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Peter S. Eagleson (Massachusetts Institute of Technology, Cambridge, Massachusetts, Author's closure)—The author is indebted to Wiegel and Danel for their constructive and informative discussions.

With regard to the work of De, it is interesting to note the results of recent experiments by *Housley* and *Taylor* [1957]. Recognizing, as De showed, the applicability of the cnoidal theory to waves of low d/L but also recognizing its awkward form for computational purposes, they compared measured celerities in the region of low d/L values with those given by the convenient small amplitude theory of Airy on the one hand and the equally convenient solitary wave theory of Boussinesq on the other. As d/L decreases, the celerity by the oscillatory theory diverges from and that by the solitary theory converges to the measured value. The point of equal error by the two theories serves to delineate the zone of applicability of each theory and further, to define an equivalent wave length for the solitary wave. Once again, however, the maximum error may become severe for large H/L.

With respect to application of the Biesel correction to the third order celerity of Stokes, it must be remembered that the range of d/L covered by the author extended to the very low value of 0.05 while that of Suquet and Wallet was limited to values above 0.2. As was pointed out by the author, waves depart from the 'Stokian' form at these low d/L's (particularly in shoaling water where symmetry is lost) and thus should not be expected to follow even the corrected third order theory. Wiegel makes this point clear in his thorough discussion.

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Discussion of "A Statistical Analysis of Hiran Measurements"

BY JOSEPH L. STEARN AND ERNEST J. PARKIN

[*Trans.*, **37**, 665–668, 1956]

George R. Woodring (1373rd Mapping and Charting Squadron, 1370th Photo-Mapping Group, Palm Beach Air Force Base, Fla.)—The statistical approach to acceptance criteria for Hiran missions described by Stearn and Parkin results in the conclusion that one part of the rejection criteria used by the United States Air Force Hiran organization is too stringent and causes missions to be rejected which are actually acceptable. Criterion 2, the part in question, specifies that four of the six line crossings in each altitude group shall not deviate from the group mean by more than 0.003 mile.

Current mission data do not support this conclusion, however. Of 106 missions flown during Phase III of the North Atlantic Tie, Project 53 AFS-1, only one was rejected because it contained an altitude group where the limits of Criterion 2 were exceeded. This measurement was made over a known distance between stations located on the west coast of Greenland; erratic measurements were expected because of extremely rough terrain surrounding the sites. Nine of the 106 missions were rejected for excessive spread between the group means (Criterion 1); of these, eight were within the limits of Criterion 2. Seven contained altitude groups where all six crossings were within 0.002 mile of the group mean.

It is unfortunate that more current mission data were not available for the subject analysis; the missions actually used were flown during Projects 50 AFS-7 (March 1951–April 1953) and 54 AFS-5 (March 1954–November 1954).

The experimental model, AN/APN-3 (XA-3) of the present airborne equipment was used throughout Project 50 AFS-7. Extensive changes were made in the production model of this equipment, AN/APN-84, which was then used throughout Project 54 AFS-5. Significant changes in the operation and design of this equipment have been made by the U. S. Air Force since that time. For example, in the latter part of 1955 circuitry was

added to the airborne set which regulates the voltage at the receiver, thus greatly increasing the operator's ability to precisely maintain constant amplitude of the receiver output. This has apparently reduced the number of missions which fail to meet Criterion 2 to an insignificant number; consequently, it seems that the problem under investigation no longer exists.

Some method of identifying an inaccurate measurement is definitely needed; however, there is some question about the merit of a purely statistical approach since this assumes normal distribution of the errors. The Hiran system is subject to systematic errors from various sources. Aircraft heading and backlash in the mechanical linkage between the indicator and recorder are two of the more well defined. The allowable backlash in the rate and drift gear trains alone is large enough to reflect the major part of the deviation within the altitude groups. These errors possibly could be minimized by changes in operational procedure; however, once recognized, it is easier to eliminate them by an averaging process. Error in the determination of aircraft altitude and changes in the setup of the equipment are likely to cause additional systematic errors. The fact that a great many more missions have been rejected for not meeting the criterion for spread between the groups than for deviation within the groups would seem to indicate the undesirability of assuming a normal distribution for individual line crossings within a Hiran mission.

The big problem currently facing the Hiran organization is in precisely identifying an inaccurate mission using only the observed data. The internal mission consistency appears to be irrelevant for all practical purposes, since almost all missions meet the criteria; however, the Hiran system, like any other observational technique, occasionally produces a wild measurement. When this occurs, the mission data are usually well inside both criteria; however, the distance may contain an error of excessive magnitude. These measurements are not isolated until a least squares adjustment of sufficient network complexity to afford a strong solution is performed. This is the method actually used during project operations for selecting the majority of the reflights, and may be considered as a check equivalent to the triangle closure used in triangulation. Although not completely satisfactory from an operational standpoint, it is the only known method of isolating an inaccurate measurement with any degree of dependability.

Joseph L. Stearn (U. S. Coast & Geodetic Survey, Washington, D. C.; author's closure)—The purpose of the paper was to indicate the desirability of using statistical techniques in testing for significant differences in observations. It is believed by the writers that the study of observations by the methods of mathematical statistics is preferable to the restraint of the observations by predetermined criteria of acceptance and rejection limits.

The Hiran system is subject to random errors and systematic errors. The random errors are reduced by averaging a sufficient number of observations while it is axiomatic that systematic errors cannot be eliminated by an averaging process.

Woodring states that the problem no longer exists inasmuch as improvements have been made in the equipment. The basic problem still exists, namely, is a given mission acceptable or should it be reflown; the fact that more missions now meet Criterion 2 does not eliminate the desirability of statistical analysis. The Student t test for example, involves both the difference of means and standard deviation as a ratio in the study of significant differences.

It might also be pointed out that running a mission in two groups of six each at two different altitudes on the same day may produce good results, acceptable either by significance tests or by predetermined criteria but at the same time such a technique can result in observations too highly correlated and consequently less desirable than observing one group on one day and the second group on another day under different environmental circumstances.

Statistical tests in many cases assume a normal distribution; however in case of distributions which are not normal, there are procedures for testing the significance of the differences. See for example *Mann* and *Whitney, Annals of Mathematical Statistics*, 1947, p. 50.

Discussion of "A Floating Lysimeter and its Evaporation Recorder"

K. M. KING, C. B. TANNER, AND V. E. SUOMI

[*Trans.*, **37**, 738–742, 1956]

L. L. Harrold and F. R. Dreibelbis (Soil and Water Conservation Research Division, Agricultural Research Service; received February 26, 1957)—The authors should be commended for designing an inexpensive weighing lysimeter which seemingly has good possibilities in evaluating evapotranspiration under relatively natural conditions. However, some clarification is needed of their statements regarding the 'effective area of lysimeters' and the reduction of evapotranspiration caused by hay-cutting, border effects, and microclimate.

The authors place great emphasis on the effective area of a lysimeter and indicate that their floating pan has minimized the possible effect of variations in effective area. Furthermore, they attribute part of the reduction in evapotranspiration after hay cutting to "cutting back of foliage which overhung the lysimeter wall" and the possible effect of the tank rim on the micro-climate of the lysimeter surface.

The effective area of their lysimeter was determined by a heat-budget calculation based on measurements of several factors. Apparently, these are made quite close to the top of vegetation before cutting and at greater distance after hay cutting. The error bands on Figure 5 are quite narrow. Can it be assumed that the area under measurement is unaffected by different atmospheric conditions outside the lysimeter area and is it possible to measure all factors in the heat-budget equation accurately enough to throw all differences and errors into the determination of a lysimeter area? Can it be concluded that all lysimeter results are unreliable unless such a calibration is made? Is it assumed that the atmospheric and other measurements made in the heat-budget method are more reliable than those made on the lysimeter?

It is not clear why some or a major part of this reduction in evapotranspiration was not attributed to the removal of the leaf area at hay cutting. It appears obvious that the removal of hay reduces the leaf area to such an extent that there is considerably less transpiration than before cutting. On the Coshocton lysimeters [*Harrold* and *Dreibelbis*, 1951], the rate of evapotranspiration which is reduced at hay cutting resumed its high rate about 10 to 15 days later, long before the vegetation laps over the border, either from the inside or outside. It is expected that the Coshocton lysimeter border effect is very small most of the time. In fact, it has often been difficult to obtain photographs to show the lysimeters since the border was imperceptible. Figure 6 shows corn in July on lysimeter Y102C at Coshocton. The outline of the border is shown by white line.

The border effect on the floating lysimeter of five-foot diameter might be evaluated for comparison purposes as 0.80 foot of border per square foot of lysimeter area. That for the Coshocton lysimeters is 0.46 foot of border per square foot of area. The width of uncropped border at Coshocton is considerably larger than that of this lysimeter. Sometimes it is visible, but often it is not as shown in Figure 6. It is not impossible that the effective area of the lysimeter and micro-climate at the land surface may be factors in this water-loss change. But this paper indicates that these factors were the only ones that change after hay cutting and that leaf-area reduction had little or no effect on evapotranspiration.

It should be emphasized that when lysimeters are used primarily for studying soil-water-plant relationships, the lysimeter should consist of a block of soil with undisturbed structure and should provide for surface runoff. The use of Plainfield sand placed in 'filled-in lysimeters' probably entails

FIG. 6 – Weighing lysimeter area

no serious errors. The use of a relatively shallow layer of soil over the air chamber would seem to be serious for alfalfa-brome, although the authors state "the decrease in rooting volume is not serious." Would not this shallow depth of soil over the air chamber tend to produce a border area especially with alfalfa brome?

Even if the floating lysimeter may involve errors due to shallow filled-in soil, and no provision for surface runoff, this type of lysimeter may serve to supply much useful information. Investigation and discussion of the problems associated with the measurement of evapotranspiration are, indeed, to be encouraged.

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Harrold, L. L. and F. R. Dreibelbis, Agricultural hydrology as evaluated by monolith lysimeters, *U. S. Dept. Agr. Tech. Bul. 1050, 84-90*, 1951.

D. B. Krimgold (Buckhorn Farm, Woodbine, Md.; received April 19, 1957)—The lysimeter described in this paper represents a decided step toward the solution of a very important and extremely difficult problem—that of measuring evapotranspiration. For a long time the Coshocton weighing lysimeters were the only ones that could be considered to give a close approximation of actual evapotranspiration. It was their prohibitive cost that kept them unique for so long.

In the middle forties when the Cold War began, a group of hydrologists from the Soviet Union visiting in this country tried unsuccessfully to visit the Coshochton project and to inspect the lysimeters. They did, no doubt, obtain copies of the several papers describing the construction and operation of these installations. It was therefore with more than ordinary curiosity that the writer of this note followed the Russian literature on the subject. It was in O. V. Popov's report on the conference on evaporation held in March 1952 in Leningrad under the auspices of the State Hydrologic Institute that the first reference appeared to a weighing lysimeter in the USSR. This cylindrical lysimeter 2.52 m (8.5 ft) in diameter, 54 sq ft in area and two meters (6.5 ft) deep was installed at the Valdai Hydrologic Laboratory in 1950. It is referred to as the "Large hydraulic evaporimeter" (BGI) and is considered the standard with which all other measurements and determinations are compared. A detailed description of the installation was given in 1953 in a monograph by V. A. Urivaev which the writer has not yet seen. In a more recent (1954) report, 140 pages of which are devoted to studies of evapotranspiration, the lysimeter is described as "a hydraulic balance with a varying weight. . . . The sensitivity is 50 gm for a total weight of 40 tons. . . . Another more important feature of this evaporimeter is that small and large changes in weight are determinable with the same high absolute accuracy. . . . In this hydraulic evaporimeter changes in moisture content of the soil monolith are determined by its vertical displacement relative to the water level in the tank in which it floats. . . . This displacement is recorded by means of three microlimnigraphs giving values of evapotranspiration to the nearest 0.01 mm."

It is rather significant that the list of references (12 in all) of the King, Tanner, and Soumi paper does not include a single one by Russian workers. Is it possible that the authors of this paper know nothing about the large amount of very important work being done in this field in the Sovient Union? It should be pointed out that in addition to the BGI, the State Hydrologic Institute of the USSR developed also what is known as the "Small scale hydraulic soil evaporimeter" (GPI-51). This lysimeter is similar to the BGI but is only 53.2 cm in diameter and 1.25 m deep. The GPI-51 was subjected to exhaustive tests and found suitable for first order hydrometeorological stations and for scientific institutions engaged in measuring evapotranspiration.

K. M. King, C. B. Tanner, and V. E. Suomi (University of Wisconsin, Madison, Wis., *K. M. K.* now at Ontario Agricultural College, Guelph, Canada; Authors' closure)—The authors feel that the definition of 'effective area' of a lysimeter is not clearly understood. We define the effective area as equal to the volume of water lost from the lysimeter divided by the average depth of water loss from the surrounding field over the same period. To assume that the area of the lysimeter tank is the effective area is to assume that the lysimeter tank is a perfect sample of the average microclimate, vegetation, and soil conditions of the field. We indicate that the lysimeter sample can change simply by cutting the vegetation. Among other changes in the vegetative cover, the contribution of overhanging foliage in and outside the tank to the effective area may be changed by cutting. Furthermore, cutting exposes a tank boundary in which no soil or vegetation exists and this can change the microclimate in the lysimeter with respect to the surroundings.

In order to determine the effective area, an independent measure of evapotranspiration is needed. This may be done over a long period by adequate and accurate soil sampling. We chose the heat budget in order to determine the sampling error of the lysimeter for a shorter period. To do this, two basic questions must be answered: (1) Does the heat budget measure the evapotranspiration? (2) Is the heat budget likely to be more representative of the surrounding area than the lysimeter? The answer to the first question is given by the fact that the ratio,

$$\frac{E_{ly_s}\ \text{(Lysimeter evapotranspiration)}}{E_{HB}\ \text{(Heat budget evapotranspiration)}}$$

is constant within ten per cent for a given crop cover over a wide range of weather conditions and stability from August 19 to September 7. Hence, whatever each is measuring is likely to be the same thing. With regard to the second question, the scale of the surface variability varies from a few centimeters (leaf size) to about a meter (the size of cover patchiness in alfalfa). Since the heat budget measurement is averaged over a 15-m path, and since each measurement made in the path is an average for a space upwind from the point of measurement, it would appear that the heat budget measurement is a better sample. As far as sampling is concerned, it would be helpful to make the heat budget measurements some distance above the surface since this would represent a larger distance upwind. However, in order to minimize the horizontal divergence of heat, heat storage, and possible bouyancy effects, it is better to make the measurements as near to the surface as possible. These two requirements are antagonistic. In our case, all measurements were made less than 1.05 m above the ground. Taking only a 20 to 1 ratio for the upwind distance sampled (a very conservative estimate), we see that the total area sampled is about 150 sq m. This compares very favorably with the two square meters of the lysimeter. The change in height of sampling that was introduced by cutting the hay (about 30 cm) would introduce small error in the heat budget measurement.

With regard to the comment by Harrold and Dreibelbis about the error band in Figure 5, we apologize for not making more clear that this is the maximum error in the ratio which would arise from lysimeter and heat budget instrument error. If we had a better independent measurement of evapotranspiration to evaluate sampling error the paper we have presented would be pointless.

TABLE 1 – *Data before and after cutting hay*

Date	Net radiation minus soil heat flux (heat available)	Air temp.	Dew point	Wind	Heat budget evapotranspiration
	langley	°C	°C	mi/hr	mm
1955					
Aug. 20	196	30.7	17.6	9.8	4.34
Sept. 9	188	30.4	9.0	12.6	2.56

Figure 5, which shows the change in the ratio (E_{ly_s}/E_{HB}), cannot show the decrease in absolute value of the evapotranspiration when the hay was cut. The data given in Table 1 for the 09h 00m to 16h 00m period on August 20, 1955 (before hay was cut) and September 9 (after hay was cut) show that the absolute value of evapotranspiration was decreased after the hay was cut, even though general meteorological conditions were such as to expect greater evapotranspiration, all other things (such as crop cover) being equal. The day after the hay was cut, the evapotranspiration from the heat budget was only 60 pct that on August 20. However, if the lysimeter alone were considered, the evapotranspiration would be only 40 pct that on August 20.

Harrold and Dreibelbis are correct in stating that the lysimeter which has a small ratio of border to total area is better than one where this ratio is large. However, it is not the ratio of border length (perimeter) to lysimeter area as they suggest, but it is the uncropped border area to lysimeter area which is important since the border area affects the representativeness of the microclimate in the tank.

If we were to build this lysimeter again, we would use the styrofoam block design for buoyancy as was suggested in the article in order to eliminate the shallow root zone over the air chamber. In the measurements presented, this difficulty was not important. With frequent irrigation, the soil moisture stress was maintained at a low level everywhere in the tank and in the surrounding field, and moisture did not limit evapotranspiration.

The authors have never proposed that this lysimeter is suitable for drainage research and for evapotranspiration measurements when moisture stress becomes limiting. These measurements require deep and large-area monolith lysimeters such as those at Coshocton. This lysimeter is useful for evapotranspiration measurements in which the the lysimeter and the surrounding field are well irrigated. We re-emphasize the importance in all

lysimetric evapotranspiration measurements that the lysimeter be representative as possible (p. 738 of our paper). Even with considerable precaution to obtain representativeness, there is still the possible sampling error, and this can be accounted for only by an independent measurement of the evapotranspiration that determines the effective area of the lysimeter.

The authors were unaware of the hydraulic evaporimeters in Russia cited by Krimgold.

Discussion of "Application of the Modified Einstein Procedure for Computation of Total Sediment Load"

BY K. B. SCHROEDER AND C. H. HEMBREE

[*Trans.*, **37**, 197–212, 1956]

Emmett M. Laursen (Iowa Institute of Hydraulic Research, State University of Iowa, Iowa City, Iowa, received Aug. 30, 1956)—Basically, any theory consists of a set of assumptions and various conclusions which are logically derived therefrom. An assumption, as the term is to be used here, may be based on an observed fact or relationship, a definition, an undefined (but generally accepted and understood) concept; or it may be based on a postulated relationship which has not been observed and may not even be directly observable. The conclusions of a theory in the physical sciences are, of course, intended to agree with and to predict observable facts. If a theory does not thus coincide with reality, it is eminently proper to examine the assumptions and the logical structure of the theory and, if possible, to modify the assumptions or correct the logic so that the conclusions do agree with observed facts.

This paper and the USGS publication by *Colby* and *Hembree* [1955, see list at end of paper here discussed] are ample evidence that the results of the Einstein procedure for the computation of total sediment load does not agree with observation. In neither of these papers, however, can any indication be found that an attempt has been made to examine critically the theory upon which the procedure is based. Therefore, a critical examination of the pivotal points of Einstein's development is needed in order properly to evaluate the proposed modifications. Only by explicitly stating the original assumptions and outlining their consequences can the effect of the modifications be placed in clear perspective.

Einstein's evaluation of the total sediment load depends first of all on his relationship for the rate of bed-load movement. In the development of this bed-load relationship the assumption is made that sediment particles move in discrete steps and that the step length is a constant times the diameter of the particle. A continuity equation for an area of the bed of unit width and one step long can be written. All particles coming to rest in this area must have started their individual steps upstream therefrom; moreover, all particles coming into this area must come to rest there. The number of particles coming to rest is then determined by dividing the rate of movement of a particular size of sediment (expressed in dry weight) by the weight of a single particle. If no erosion or deposition is to occur, an equal number of particles must begin a step in the same area. The number of particles beginning a step is determined by multiplying the number of particles on the surface by the number of times each particle, or its replacement, begins a step in unit time. Using the notation of *Einstein* [1950]

$$\frac{q_B i_B}{A_2 D^3 s_s g} = \frac{A_L D i_b}{A_1 D^2} p_s \qquad (6)$$

where q_B is the total rate of bed-load movement, i_B is that fraction of the total movement consisting of particles of diameter D, A_2D^3 is the volume of a single particle, s_s is the density of the sediment, g is the gravitational acceleration, A_LD is the length of a step, i_b is the fraction of the bed sediment of the particular size, A_1D^2 is the area of the bed associated with each particle, and p_s, although referred to as a probability of removal, is the number of times each particle or its replacement moves in unit time (or the reciprocal of the time elapsed between the beginning of the step of a particle and the beginning of the step of its replacement). Eq. (6) follows logically from the assumption of constant step-length and the principle of continuity.

A particle at rest on the surface will move only if the fluid forces on that particle are greater than its resistance to movement. Einstein postulated that the fluid forces could be expressed as a lift force proportional to the square of the velocity at an elevation of 0.35 D above the bed and the resisting force by the buoyant weight of the particle. In a turbulent flow the fluid forces will vary with time in a random manner which can be described by the normal-error law. The probability that a particle will move is then the probability that the immersed weight of the particle will be less than the lift force on the particle (or that the ratio of the weight to the lift will be less than unity)

$$\frac{W'}{L} = \frac{g(s_s - s_f)A_3D^3}{c_L s_f \tfrac{1}{2} u^2 A_1 D^2} < 1 \qquad (7)$$

where W' is the immersed weight of the particle, L is the instantaneous lift, s_f is the density of the fluid, c_L is a lift coefficient, and u is the velocity 0.35 D above the bed. If the instantaneous lift is considered as the sum of an average lift and an instantaneous deviation from that average, then

$$L = \bar{L} + L' = \bar{L}\,(1 + L'/\bar{L})$$

and the standard deviation of $L'/\bar{L}$ can be written as

$$\eta_0 = \left[\frac{\sum_0^n (L'/\bar{L})^2}{n}\right]^{1/2}$$

The probability of L being greater than W' is then, according to the Gaussian probability function

$$p = 1 - \frac{1}{\sqrt{\pi}} \int_{1/\eta_0(-W'/\bar{L}-1)}^{1/\eta_0(+W'/\bar{L}-1)} e^{-t^2} dt \qquad (8)$$

where p is the desired probability and t is a variable of integration. Tables of this integral are generally available. If η_0 is ½, as suggested by Einstein, the variation of p with $W'/\bar{L}$ can be easily computed:

$W'/\bar{L}$	1	½	¼	⅛
p	0.50	0.92	0.98	0.99

In Einstein's development u is related to the shear on the bed by the logarithmic velocity distribution. Only the shear due to the particle roughness, however, is considered. In addition certain correction coefficients are applied to the lift to account for the relative size of the laminar sub-layer and the effect of sand mixtures.

In order to continue the analysis, a relationship is postulated between p_s, the number of times a particle or its replacement begins to move in unit time, and p, the probability that a particle will move because the instantaneous lift is greater than the immersed weight. The ratio of these two quantities is assumed to be proportional to the time that it takes a particle to fall its own diameter in still water.

$$\frac{p}{p_s} = A_3 D/v_s = t_1 \qquad (9)$$

That the ratio of a quantity dependent on the flow conditions to a quantity dependent on the rate of transport would be proportional to a value variant only with the particle size, although possible, seems extremely unlikely. Combining Equations (6), (8), and (9) the rate of transport of a particular size would be equal to a constant (for the particular sediment) times p

$$q_B i_B = \text{const}\left[1 - \frac{1}{\sqrt{\pi}} \int_{(1/\eta_0)(-W'/\bar{L}-1)}^{(1/\eta_0)(+W'/\bar{L}-1)} e^{-t^2} dt\right] \qquad (10)$$

Eq. (10), however, would indicate an almost constant rate of movement if the average lift were greater than twice the immersed weight. To obtain an increasing rate of transport with increasing shear, Einstein considered the effective step length to increase with p. The argument followed from the idea that if the lift exceeded the immersed weight at the time and place a particle would otherwise have come to rest, the particle would continue to move in another step. The effective length of a step $A_L D$ can then be shown to be the constant step-length λD divided by $(1 - p)$, and the rate of transport becomes

$$q_B i_B = \text{const}\ p/(1 - p) \qquad (11)$$

As p approaches 1, the rate of transport obviously approaches infinity. The fallacy of the argument can be shown by considering the number of particles which begin to move. If a particle which is about to end a step instead begins a new step, a particle already at rest will not begin a step. For every particle that does not stop a particle does not start. If this argument is followed through, the number of particles in movement times the effective length of the step will be found to be constant; thus, the rate of transport will not increase with the increase in length of step. If a step length

dependent on the flow conditions is desired, the assumption of a constant step-length must first be discarded and a new assumption substituted. Not only would this be both proper and possible, but, in addition, an explicit statement of the new assumption would be more likely to receive its due critical examination.

Einstein's evaluation of the suspended load depends on the evaluation of a concentration at a reference level $2D$ above the bed. The concentration at this level is equated to the rate of bed-load movement divided by $2D$ times the velocity at the edge of the laminar sub-layer. The diffusion or mixing process of the turbulent flow is considered to be sufficient to lift the bed load into suspension. The relative distribution of the suspended sediment then follows the usual solution with the exception that in the exponent z of the concentration-distribution equation only the shear velocity associated with the particle roughness is considered.

$$z = v_s/0.4u_*'$$

Since u_*' is less than the total shear velocity u_*, z takes on a larger value and the indicated distribution is less uniform than would otherwise be the case. Most investigators, on the other hand, find that the total shear velocity must be increased by a factor of about 1.5 to describe properly the distribution of suspended sediment.

The purpose of this examination of Einstein's theory has been to state clearly the assumptions involved which can be seriously questioned. A comprehensive examination would consider all assumptions; however, those not mentioned here would probably find general acceptance. The questionable assumptions may be summarized in the writer's opinion of their order of importance: (1) The assumption that the ratio p/p_s is proportional to D/v_s. (2) Either the original assumption that the step length is a constant proportional to the diameter of the particle no matter what the flow conditions or rate of movement, or the alternate assumption which increases the original constant step length through division by $(1 - p)$. (3) The assumption that the mixing action of the fine-scale turbulence is sufficient to lift particles very close to the bed into suspension. (4) The assumption that the velocity of the particles moving as bed load is equal to the velocity at the edge of the laminar sub-layer. (5) The assumption that only the shear velocity associated with the particle roughness should be considered in the evaluation of the exponent z of the equation of sediment concentration distribution. (6) The assumption that lift forces are primarily responsible for bed-load movement. (It is of interest here that the ratio of the critical tractive force to the actual tractive force τ_c/τ_0 can be substituted for $W'/\bar{L}$ without any essential change in the final relationship.)

In view of the tenuous nature of these assumptions, the modifications of Einstein's theory advocated by the authors seem to be either mere expediency or an arbitrary forcing of the calculated values to fit measured data. No issue is taken by the writer with the two modifications that can be termed expedient: the expansion of the finer fraction of the measured suspended load to the full depth of flow, and the determination of the shear velocity from the measured mean velocity. The first of these, however, is itself almost a rejection of Einstein's method of evaluation, since the integral values of the concentration distribution are used only to establish the correction coefficient to be applied to the measured suspended load.

The two methods proposed to determine ψ_m appear to be both expedient and arbitrary. In effect, both use an average value of the correction coefficients suggested by Einstein, the computational procedure thereby being simplified. No justification, however, is advanced for the choice between the two values of ψ_m so determined or for the division by a factor of two of the rate of transport then obtained from Einstein's basic curve other than that the end justifies the means.

Determination of a z value which will make the calculated suspended load agree with the measured load is, of course, possible. Only if the reference-level concentration is correct will the z value thus determined correspond to the correct distribution of sediment. That this arbitrary modification can force agreement is no criterion for its validity. Equating the z values for other size classes to the product of the z value as determined above and the 0.7 power of the applicable fall-velocity ratios seems again arbitrary (and, to the writer, gives evidence only that the size distribution of the suspended sediment at the reference level as determined by Einstein's procedure is incorrect.)

The modifications advocated by the authors appear basically to be correction factors to be applied to various steps in Einstein's computation procedure. That fair agreement is then found between the measured data used to determine these

factors and the computed values is to be expected. Einstein also suggested similar, but different, correction factors in order to obtain agreement with measured data. It must be realized, however, that unless valid logical reasons can be advanced to justify such correction coefficients, neither the original nor the modified procedure for the computation of the sediment load can be applied with confidence to a different stream for which measurements of the sediment load is lacking.

Lloyd C. Fowler (Missouri River Division, Corps of Engineers, Omaha, Nebr., received Sep. 4, 1956)—This interesting paper is a vaulable extension of the USGS Water Supply Paper 1357, [*Colby* and *Hembree*, 1955] in which the modified Einstein procedure for computation of total sediment load was first presented. The magnitude and importance of the unmeasured sand load in shallow streams is well illustrated. In the case of streams that are not shallow, however, the unmeasured sand load may be of minor concern especially when the sand transported is predominantly fine. Computations of the total silt and clay transport of a river can be made easily and accurately by applying the concentration of silt and clay as found by depth integration to the total discharge at the measurement vertical. This is so because the finest particles are uniformly distributed in the vertical.

The important fact remains, however, that in alluvial rivers the total sand load cannot be measured with existing sampling equipment and, therefore, must be computed. A recent series of computations to determine the total suspended sand transport in the Missouri River enabled the results obtained by depth integration alone and by the modified Einstein procedure to be compared with the 'actual' transport. The series of field measurements used in the computations was obtained by the Omaha District, Corps of Engineers, as part of a continuing study of the sediment transport characteristics in the Missouri River.

The portion of the field data used in the computations consisted of samples of the suspended sediment concentration and bed material, and measurements of water velocity and temperature at a number of measurement verticals spaced across the river channel. Standard P-46-E sediment samplers and Price current meters were used. At each measurement vertical two depth integrated suspended sediment samples were obtained. Then seven or more point suspended-sediment samples and point velocity measurements were taken to define the sediment and velocity distributions at that vertical.

As defined by the field measurements, the distributions of suspended sand concentration and velocity were integrated to within a very small distance of the bed (approximately two grain diameters) to define the 'actual' suspended sand transport at each measurement vertical. The suspended sand concentration by depth integration was multiplied by the total discharge at that measurement vertical to give the suspended sand transport by depth integration. In all cases the unsampled depth was less than ten per cent.

Comparison of the suspended sand transport as determined above showed that depth integration gave values that are slightly smaller than the 'actual' transport. In 29 measurements, the total suspended sand transport averaged 93 pct of that determined by point integration. The comparisons were very good for the fine grain sizes as was to be expected, but in the coarser grain sizes the transport values given by depth integration were too low.

In relatively deep streams the per cent of depth unsampled by depth integration is small and from the foregoing comparison it would appear that the total suspended sand may be simply and fairly accurately determined by extrapolating the suspended sand concentration as found by depth integration over the total depth. This would not be the case, however, when significant amounts of very coarse sand were being transported.

Using the same field data described above, particularly the depth integrated samples, computations of the suspended sand transport were made according to the modified Einstein procedure set forth by *Colby* and *Hembree* [1955] and outlined in this paper. The suspended sand transport was obtained from the modified procedure by first computing the total load and then subtracting the value $i_B Q_B$ (given by the equation near the top left of page 201). The result was assumed to be the suspended sand transport even though it was recognized that the value of $i_B Q_B$ in the modified procedure was not a true value of the bed load transport.

Comparison of the suspended sand transport at 29 verticals and four cross sections showed that the modified procedure gave values that ranged from 8 to 108 pct higher, averaged 34 pct higher, than the 'actual' transport. The difference in suspended

sand transport was to a large extent confined to the larger grain sizes, that is, sizes above 0.15 mm (0.00049 ft).

This consistently high result of the modified procedure indicated that some empirical portion of the method needed adjustment to apply to the Missouri River. As the authors point out: "Certain functions that have been defined empirically must be defined on a theoretical basis before the procedure can be used on all streams with the expectation of determining accurate loads." Some of the empirical characteristics set forth by *Colby* and *Hembree* [1955] and again in this paper which differ from those observed on the Missouri River follow.

(1) Rubey's fall velocity for sediment used in the modified procedure does not represent the fall velocity of Missouri River sands as determined in the laboratory. As a result, the exponent z for the vertical distribution of suspended sediment in the Missouri River is approximately proportional to the first power of the measured fall velocity.

(2) The von Karman constant k, which is part of the value 5.75 in (2) is assumed to be 0.4, while over 400 velocity distribution measurements on the Missouri River show it to vary from 0.16 to well over 0.4, with about 90 pct of the values less than 0.4. The median for all measurements is 0.28.

(3) In (3), $Y(B/B_z)^2$ is a constant for any one flow, but ξ varies inversely with the grain size. On the Missouri River the product of the correction factors $\xi Y(B/B_z)^2$, for grain sizes greater than 0.3 mm approximates 0.5. It increases to about 1.5 for a grain size of 0.1 mm. There are, of course, variations in these figures depending on the actual flow. The modified method assumes the value of $\xi Y(B/B_z)^2$ to be 0.4 for the larger grain sizes and about one for the smaller grain sizes.

While working with the modified procedure it became apparent that use of the large grain-size intervals suggested by *Colby* and *Hembree* [1955] made the selection of the reference grain size quite critical. That is, a change from one size interval to the next size interval higher or lower in the determination of z_2 would produce a large change in transport. A smaller interval in sizing (such as a standard square root of two sieve series) greatly reduced the resulting change in transport when z_2 was determined from two adjacent size intervals.

Time has not permitted a detailed study to determine the effect of changing some of the empirical constants as noted above. However, in spite of the consistently high results for the suspended sand transport the modified Einstein procedure gives what are considered reasonable results for the total sediment load, bed load plus suspended load, in the Missouri River. This is rather unexpected when it is noted that the modified procedure was derived for steep, shallow sand-bed streams.

K. B. Schroeder (U. S. Bureau of Reclamation, Denver, Colo.) and *C. H. Hembree* (U. S. Geological Survey, Lincoln, Nebr., authors' closure —Laursen's discussion appears to be more a discussion of Einstein's original procedure for computing bed-material load than a discussion of the modified Einstein procedure. He states that this paper and the publication by *Colby* and *Hembree* [1955] are ample evidence that the results of the Einstein procedure for the computation of total sediment load does not agree with observation. It is not clear whether Laursen is referring to the modified Einstein procedure or to the Einstein procedure, inasmuch as the latter does not compute total load as Laursen seems to imply at several points in his discussion. If Laursen's statement does apply to the modified procedure, we are of the opinion that the agreement of computed total loads with measured total loads as shown by Figure 6 are ample evidence to the contrary.

Laursen correctly points out that certain of the modifications of Einstein's procedure are arbitrary; this was so stated by *Colby* and *Hembree* [1955] and in this paper. The modified Einstein procedure was designed to use information that can be measured in the field much more accurately than it could be computed by any idealized theoretical formula yet devised. The theoretical formulas have been arbitrarily adjusted to use these data effectively and thus give the practical working engineer a tool that he can use to obtain answers to problems that must be answered now and not at some future date when more valid theoretical formulas have been developed.

Laursen has stated that the variation of z to the 0.7 power of the fall velocity seems arbitrary. This statement is not correct. The z's from point samples vary on the average with the 0.7 power of the fall velocity when based on Rubey's equation. This phenomenon is evident on the Niobrara River as well as on streams that are different.

Laursen implies that the modified Einstein procedure may not be applicable to a stream other than the one for which data were used to develop

the procedure and further appears to imply that the authors were not aware of this possibility. The purpose of this paper was to show that although the procedure was developed on the Niobrara River at Cody, Nebr., computations for four additional streams gave good comparisons with the measured total load without recourse to additional 'correction coefficients.'

The authors are fully aware that the modified Einstein procedure is not the complete and final answer to the problem of obtaining total loads and that the procedure should be used only in conjunction with good engineering judgement. However, we do feel that it is a tool that can be used to advantage by the engineer and an idea that can be developed further along more valid theoretical lines that are, as yet, undivulged.

The discussion by Fowler is greatly appreciated because it represented experience in actual application. It is hoped that more ideas and experience will be expressed by engineers faced with the problem of field application.

Discussion of "Effect of Various Hydro-Climatic Factors on Snowmelt Runoff"

BY VICTOR A. KOELZER AND PERRY M. FORD

[*Trans.*, **37**, 578–587, 1956]

Willard M. Snyder (Hydrology Section, Hydraulic Data Branch, Tennessee Valley Authority, Knoxville, Tenn.; received Jan. 28, 1957)—This report of an investigation to determine a multiple correlation equation for use in relating various hydrologic factors is an extremely worthwhile presentation. As the authors point out, there have been numerous papers reporting results of statistical analyses of hydrologic data. However, there have been too few papers devoted to a description of the techniques used in selecting and designing empirical equations for use in regression analysis in hydrologic studies. The recent rapid increase in the application of electronic computers emphasizes the need for increased familiarity with basic mathematical and numerical methods.

Some analytical work of the Hydrology Section of the Tennessee Valley Authority has been done using an electronic computer. The analytical approach has been somewhat different from that described by the authors and may be of interest. In addition to the economic considerations, problems were analyzed on the electronic computer in order that longer equations could be fitted to observational hydrologic data. The large number of simultaneous normal equations can be readily solved by matrix inversion on an electronic computer but are very difficult to solve with a desk calculator.

Equations containing a large number of terms result from two reasons. Except for such quantities as area-weighted rainfall, parameters were not usually combined by any system of weighting, but instead were allowed individual expression. Also, quite frequently cross products of the parameters were used where there was indication that a parameter modified the relationship of two other variables by more than a simple additive effect. Some of the basic linear equations have been summarized and their effect on the dependent variable described [*Snyder*, 1956].

Some apparent inconsistencies in coefficients result when parameters which are correlated are used as independent variables in regression analysis. This is not too serious unless the individual effect of a particular term is required. Using a weighted mean of the correlated variables appears to suppress some of their relationship to the dependent variable. Considering, for example, two independent variables, unless one of these variables can be perfectly predicted by the other there must remain some deviation from their line of regression. It is these residual deviations which may have an important relationship to the dependent variable, and the weighted mean allows only partial expression of this effect, since only one degree of freedom is allowed for the two variables.

The use of cross-product terms in a regression equation is necessary when the relationship requires a family of diverging lines, instead of a family of parallel lines. Terms of this type have been found highly significant in some studies.

Testing for significance of parameters was

usually accomplished in the Tennessee Valley Authority studies by an analysis of variance due to dropping terms from the equation. This is a powerful and versatile statistical technique since terms can be tested individually or in combination. The t-test, or σ_b/b-test, mentioned by the authors is limited to one degree of freedom; the F-test can be used with any number of degrees of freedom, equal, of course to the number of terms being tested in combination. Using this F-test, it is possible to drop collectively those terms containing correlated variables, and thus prevent one variable from assuming some of the effect of another as may happen when they are dropped separately.

The method described for selecting a particular equation from the many analyses seems subjective. For example, if a particular regression coefficient has a sign opposite to that which was logically expected, a very likely explanation would be correlation of the independent variables. However, even if a partial regression analysis did not rectify this inconsistency, if the reversal of sign was associated with a coefficient of real statistical magnitude, rather than a random variation from zero, it is difficult to see how the equation containing the term could be rejected. At any rate, if a particular term is rejected in one equation it is necessary that it be rejected in all equations in which the same system of physical logic applies, otherwise a bias could be introduced.

The computation of confidence limits about the n-dimensional surface of the multiple regression model is a statistical index of accuracy not mentioned by the authors. This is an important index when the regression model is used as a prediction device, since the confidence limits of the predicted point are based on the variance which is residual to fitting and the variance of the regression model about the predicted point. The variance of the model depends upon the deviation from respective means of all the parameters used to predict the point about which the confidence limits are being computed. Basically, the method reduces to an operation upon the invert, or covariance, matrix which is easily done by the electronic computer. It would appear that this standard statistical technique [*Anderson* and *Bancroft*, 1952, p. 202] could be used to handle the problem of the variability of the forecast due to melt-season precipitation which the authors discussed.

A disturbing question remains unanswered after a consideration of the study of various equations which is presented. If this study had been based on a rather lengthy equation containing all those forms for the independent variables in which they could have been reasonably expected to occur, there would have been left very few degrees of freedom over which to distribute the residual sum of squares. Theoretically, when the number of terms in the equation becomes equal to the size of the sample, the computation of the residual variance becomes indeterminate since both residual sum of squares and the residual degrees of freedom become zero. It is interesting speculation to consider how the authors' approach, an almost exhaustive examination of terms in different equations, might also tend to exhaust the residual degrees of freedom, leading to some indefiniteness in evaluation of residual variance.

References

Anderson, R. L., and T. A. Bancroft, *Statistical theory in research*, McGraw-Hill, New York, 399 pp., 1952.

Snyder, Willard M., *Some linear models for multiple regression analysis in hydrology*, Duplimat reproduction by Tennessee Valley Authority, Knoxville, Tenn., 20 pp., 1956.

Donald W. Kuehl (Weather Bureau River Forecast Center, Portland, Oregon; received March 1, 1957)—The authors have made a detailed study of water-supply forecast equations for their basins, and are to be complimented on the mature manner in which they have interpreted the results of their numerous statistical correlations. Such emphasis on the use of 'experience and judgment' in modifying the conclusions indicated by statistical computation has been generally overlooked in most recent papers on water-supply forecasting.

The studies verify the judgment of many hydrologists that any difference in the efficacy of snow survey and precipitation data in forecasting runoff is far overshadowed by the variation of other factors such as location of stations, number of stations, quality and period of record. As a result, statements advocating exclusive use of either variable in forecasting equations for all basins cannot be substantiated.

In general, the authors' analyses of the usefulness of precipitation were based on lumping monthly precipitation into four groups: July–September, October–December, January–March, and April–June. The use of fall and spring precipitation as independent variables in the correla-

tion is well supported by hydrologic reasoning. However, the conclusion that winter precipitation should be used by dividing it into two periods has not been demonstrated. The results of correlations by the authors give weights to October–December precipitation, varying from 60 pct to double the January-through-forecast-date precipitation. It is difficult to see how December precipitation can have true effective weight which varies from January precipitation weight by 40 pct or more. The climatological situation in these two months is so similar that any variation in true weight from one month to the next should not be excessive. One method of accomplishing this and yet weight early and late precipitation differently is to assign individual monthly weights [*Kohler* and *Linsley*, 1949].

Although the period of record is too short to attempt to derive weights by multiple regression techniques, it is possible to select trial weights which can be used to arrive at a weighted average as winter precipitation index to runoff [*Polos*, 1953; *Water Management Subcommittee*, 1953]. The weights can be applied on a trial basis to all basins of similar climate. Modification of trial weight should be done on basis of results in all similar basins.

Some investigators have found that fall or winter streamflow is a valuable index to runoff carry-over. *Peck* [1954] used average flow for one winter month for a procedure for the Blue River at Dillon, Colorado. *Nelson*, *McDonald*, and *Barton* [1953], working in the Columbia Basin, used base flow on November 1 derived from hydrograph analysis. In both cases, improvement in the forecast relation appears significant. Perhaps refinements such as these in the runoff index would give the variable the significant effect the authors feel it should have.

The authors' admonition to use sound judgment and reasoning when individually tailoring a procedure to a basin cannot be over-emphasized. Alteration of the basic procedure from one basin to the next on basis of statistical fit can result in large errors in forecasts. The hydrologist must be certain that the alterations are done to fit the hydrology of the basin and not the vagaries of the historical data. Alteration of the basic procedure on the strength of statistical fit alone results in the loss of forecast effectiveness as surely as through loss of degrees of freedom by the addition of more independent variables.

The authors have included melt-season precipitation in all recent equations on the theory that the most nearly correct weighting of the pre-melt factors will result only when all factors influencing the runoff are included in the correlation. Although this approach has provoked objections from some, it does have the backing of many hydrologists [*Water Management Subcommittee*, 1954]. This reasoning can be applied to snow measurements also. The accountability equation can be based on April 1 measurement and in forecasting practice the observed water equivalent plus mean or median accumulation from the forecast date to April 1 is used.

Combining precipitation and snow survey data before correlation is an excellent way to avoid the problem of what to do to the erratic coefficients resulting from regression computation involving highly intercorrelated 'independent' variables. The derivation of the authors' equation for weighting winter precipitation and snow survey measurements is not obvious. Since W_o and P_o are constant for the basin, the denominator is a constant and its introduction has the same effect as changing the units of observation.

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Victor A. Koelzer (Harza Engineering Co., 400 West Madison Street, Chicago 6, Illinois) and *Perry M. Ford* (U. S. Bureau of Reclamation, Denver, Colorado; Authors' closure). The interesting and constructive comments on this paper are greatly appreciated by the writers. These have served to round out the subject and to raise questions that allow clarification of some points that may not have been well explained.

Snyder has stated that the t-test, or σ_b/b test,

as used by the writers, is limited to one degree of freedom. The meaning of this statement is not clear to the writers, but it appears that the concept is not in accord with the definition of degrees of freedom that is commonly accepted. *Ezekiel* [1942; see references at end of paper] describes degrees of freedom as the number of observations less the number of constants in the regression equation. The same reference clearly illustrates that the test applies to multiple correlations. There is nothing inherent in this test that limits it to one degree of freedom.

Snyder also stated that the method described for selecting a particular equation from the many analyses seems subjective. If this statement is intended to mean that the writers allowed judgment to influence their selection, rather than mechanically choosing the equation having the highest statistical accuracy, it is quite true. For example, in practically all cases it would have been possible to select a single snow course or a single precipitation station having a better correlation than the average of several stations as used in the equations selected. However, this would have made the ultimate forecasts susceptible to possible future errors in a single observation or to unequal distribution in precipitation. It seems imperative, from a hydrologic viewpoint, that the number of measuring points in the basin be adequate to minimize such errors. Similar reasoning, based on hydrologic experience, was allowed to influence the selection in other cases. In the case of regression coefficients having opposite signs to those logically expected, the explanation could not be inter-correlation, as suggested. These occurred in such items as fall precipitation and spring precipitation, with no other concurrent meteorological items included in the same equation.

Snyder's statements seem to infer that the writers did not use the covariance matrix or inverse matrix in the analyses. Actually, this procedure was used throughout. The routine of analysis used by Snyder may have been somewhat different than used by the writers, but the basic procedures and the end results would appear to be the same.

As Snyder has stated, the remaining degrees of freedom that would have existed if all potential influencing factors had been included in one equation would have been so small that very little accuracy would have been left in the equation. However, the writers cannot understand the concern that an exhaustive examination of terms in different equations might also tend to exhaust the residual degrees of freedom. Only one equation was selected and this equation has a given number of degrees of freedom, depending only on the number of observations and number of variables. This value would be the same regardless of whether it was the only equation developed or whether a vast number of equations for the same forecast were developed independently. The writers believe that through the selection of factors and of a final equation on the basis of logic and judgment, the element of chance can be more effectively reduced than if a single trial had been depended upon to yield a forecasting equation.

The writers are pleased to have Kuehl's concurrence in the use of judgment in selection of a forecasting technique, and concur heartily with him that the exclusive use of a particular variable for all basins cannot be justified.

Kuehl stated that the conclusion reached that winter precipitation should be divided into two periods has not been demonstrated. The writers did not contend that the winter precipitation should be divided into two periods. The trials were made to find out, if possible, if some variation does exist between early and late winter precipitation, as has been suggested by some engineers. The results were entirely inconclusive and do not support any single contention. Results of analysis that have come to the writers' attention involving individual months as separate variables, have not been encouraging. The large number of variables and short periods of record could lead to biased variations larger than the 40 pct mentioned by Kuehl.

Kuehl suggests the use of one month's fall flow or the base flow at a particular time during the fall as a factor that might properly reflect antecedent conditions. The writers use four- and five-month periods during the late summer and fall as the factor. While it is recognized that the writers' factor did not reflect a satisfactory expression of this influence, we doubt that the flow on a single month or a single day will be wholly satisfactory. These would seem to be relatively small samples of the total influence and the higher statistical accuracy obtained with their use could be chance coincidence. This could make this factor susceptible to future errors when the month or day selected happens to be unrepresentative of the total period.

The use of fall and winter runoff as an influence of flood season runoff is controversial. The possible relationship can be reasoned to be either positive

or negative, and examples of both have been observed. One example of a negative relationship was the Swan River in Montana where a heavy winter runoff in 1934 resulted in depletion of the snow pack and a reduced flow during the following flood season. Base flow is undoubtedly a positive factor in flood season runoff but its small effect in most areas is often concealed by vagaries of data on major factors.

Kuehl has questioned the reasoning behind the equation used to combine snow survey and precipitation data, which was

$$I_x = (W_a P_x + P_a W_x)/2 (W_a + P_a)$$

where I_x = weighted average snow-precipitation index for year x
W_a = average snow-water content for period of record
W_x = snow-water content in year x
P_a = average winter precipitation for same period of record as for snow-water content
P_x = winter precipitation in year x

This equation will, on the average, give equal weight to snow survey and precipitation data. The case where average snow-water content is 15 inches and average precipitation is five inches can be used as an example. Snow-water content in year x will thus be multiplied by five and the precipitation by 15. Since the terms are added the departure from average in the precipitation term for the given year will carry about the same weight as the departure from average of the snow-water content term, since the absolute values of precipitation can be expected to be in the order of 1/3 that of snow-water content. The denominator is chosen to make the weighted index meaningful in quantitative terms, being in reality a weighted average of the two values. Actually, as Kuehl infers, the denominator could be selected as any other value, since it is a constant for the basin. Any change in the denominator would thus merely mean a compensating change in the regression coefficient.

Letters to the Editor

Comments on a Review by C. L. Bretschneider of "Practical Methods for Observing and Forecasting Ocean Waves by Means of Wave Spectra and Statistics," U. S. Navy Hydrographic Office Pub. No. 603, by W. J. Pierson, Jr., G. Neumann, and R. W. James

As the M of the SMB method I should like to add some comments to Bretschneider's review. I think the SMB method, at least in its earlier SM version, deserves retirement. It was first used in 1942 during the invasion of North Africa and published in 1947, and it is amazing that it should have survived so long. Its accomplishments were to organize multitudes of scattered data into a few dimensionally consistent empirical relations. I feel now that in the various SM papers we should not have tried so hard to clothe these relations into a theoretical straightjacket.

The great advance came through the spectrum analysis of swell records by *Barber* and *Ursell* [1948] in England, followed by an application of the spectrum to the forecasting problem by Pierson, Neumann, and James. I view this as a conceptual advance, and as such it has certainly cleared the air. The significant wave height of SMB (psychologically significant perhaps, but certainly not a physical entity) can be reinterpreted as a constant times the square root of wave energy, with the constant determined by the work of Longuet-Higgins, or by an earlier and often neglected work of Putz. The result can be compared to the energy under the PNJ spectrum. Bretschneider's review is devoted largely to such a comparison, but the important thing is the conceptual advance which made this comparison possible, and PNJ deserve great credit.

The basis of the PNJ method is an empirical formula for the wave spectrum proposed by Neumann. This is not a relation derived from fundamental principles. It is as misleading for PNJ to refer to a *theoretical* spectrum as for *Sverdrup* and *Munk* [1947] to have entitled their paper "*Theory* of relations for forecasting." Bretschneider's dimensional arguments against Neumann's dimensional constant C are indecisive, for what is to prevent us from multiplying by (gravity)$^{\frac{1}{2}}$ (kinematic viscosity)$^{-\frac{1}{2}}$, say? In the final analysis the appeal to observations is the only basis for judgment. Bretschneider presents a figure to show that the total energy $E \sim v^4$ (from SMB) is a better fit than PNJ's $E \sim v^5$. But this conclusion depends on the assumption that a separate relation holds for winds above 6 m/sec than for winds below 6 m/sec. I am afraid my paper on "A critical wind speed for air-sea boundary processes" *Munk* [1947] is partly responsible for this schizogony of the sea surface. All kinds of observations (including the soaring tactics of sea gulls) indicated a discontinuity at Beaufort 4 before the paper was published, but none did afterward. The work by *Cox* and *Munk* [1954] on sun glitter was directed toward finding the discontinuity, but there was no sign of it. And when *Roll* [1952] wrote his paper, "Gibt es eine kritische Windgeschwindigkeit fuer Prozesse an der Grenzflaeche Wasser-Luft?" I felt about this subject as about the little man who wasn't there. But lately *Mandelbaum* [1956] and *Lawford* and *Veley* [1956] have resurrected the problem. In all events, this is hardly a firm basis from which to decide whether the v^4 or v^5 law fits better.

Our work on mean-square slope from sun glitter [*Cox* and *Munk*, 1954] seemed to us to favor Neumann's v^5 law, but *Darbyshire* [1956] has raised some question concerning our interpretation. Certainly things need to be straightened out by critical measurements. One possibility is to measure the fully developed high-frequency (but not capillary) skirt of the energy spectrum ($\sim$(frequency)$^{-6}$ according to Neumann), and this could be done over quite small bodies of water. Snodgrass and I have concentrated on the low-frequency tail, and we may have some results to report. And if my suggestion that $C \sim g^{\frac{1}{2}}\nu^{-\frac{1}{2}}$ has any merit, one might be able to detect the roll of viscosity. *Francis's* [1956] experiments in blowing wind over syrup are pertinent in this regard.

In many ways it would have been preferable if the preparation of the PNJ manual could have been delayed a decade until these problems and others (such as wave directionality) had time to settle down. But the valid reply is that there is a need now for wave forecasts, and one has to do the best he can. Certainly the PNJ method is a vast improvement over what Sverdrup and I worked out in the war years.

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The review of H. O. Pub. 603 by Bretschneider contained in the April 1957 issue of the *Transactions* is more like a scientific article attempting to set forth the merits of the v^2 law for the significant height of a fully developed sea as opposed to the $v^{2.5}$ law used in H. O. Pub. 603 than it is a review of our work. As such it should be answered by scientific papers and not by a letter to the editor. However there are certain points in Bretschneider's review which we would like to answer at this time. Other points will be more adequately covered by papers currently in preparation.

The comments of W. H. Munk concerning the review of our work by Bretschneider are greatly appreciated. The value of the SMB method as a tool for forecasting waves when it was the only method available is not to be questioned.

It would be possible for us with the hindsight given by spectral methods to question the entire theoretical structure of the SMB method such as the very choice of the dimensionless parameters used and the theoretical foundations of the method of swell forecasting. The SMB method has always been rather vague in giving methods for forecasting how long a swell will last and how to forecast the decrease in height of a dead sea. However, since we believe that several new concepts first used in our methods have eliminated these difficulties there is little point in writing on this subject at the present time.

To us, and this is mainly an aside with reference to Munk's remarks, any theory is simply an attempt to assemble all known facts about a subject in an understandable whole, deduce from these facts general laws that must be followed, and predict what will happen from these laws. As such, any theory is always subject to either verification or refutation by continued research, as stated in H. O. Pub. 603 a number of times, and it would be futile to wait until all controversy had ceased before publishing one's results.

The theoretical spectrum derived by *Neumann* [1954] is thus an attempt by theoretical methods to deduce the shape of the frequency spectrum of a fully developed sea. It is not an attempt to explain why the spectrum has that shape nor is it an attempt to show that the log $(H/\bar{T}^2)$ versus $(\bar{T}/v)^2$ plot must have certain properties. As in any scientific investigation, certain observed facts were used to derive by mathematical means a general law about the spectrum of the waves. For the purposes of wave forecasting this is sufficient if the theoretical form of the spectrum is correct.

With reference to Bretschneider's review we would like to make the following points:

(1) In the development of the wave spectrum, the following relationship between the apparent wave height H_T and the apparent wave period $\bar{T}$ was used

$$H_T = \text{const}\,\frac{g\bar{T}^2}{2\pi}\,e^{-(g\bar{T}/2\pi v)^2} \tag{1}$$

Bretschneider refers to this equation and states it correctly in his review. However he has misinterpreted the meaning of this relationship. H_T was defined in the original derivation by

$$\frac{\delta U_T}{dT} = \frac{1}{8}\,g\rho(H_T)^2 \tag{2}$$

that is, in terms of the spectral energy density $\delta U_T/dT$[erg/cm² sec]. Hence, $(H_T)^2$ has the dimensions cm²/sec, and the constant in (1) is not dimensionless as was stated by Bretschneider. Moreover, there is no interchange of energy and power since the basic Eq. (2) represents spectral energy density. This seems to be another misunderstanding by Bretschneider of the basic concepts which led to the derivation of the energy spectrum. It is seen that according to (2), $(H_T)^2$ represents the square of the spectral wave height for a given period interval ΔT. From (1) and (2) it follows that

$$\delta U_T = C\rho\,\frac{g^5}{32\pi^2}\,T^4 e^{-2(g\bar{T}/2\pi v)^2}\,dT \tag{3}$$

and that the 'loss of dimensions' claimed by Bretschneider do not occur. C must have the dimensions sec^{-1}, and this seems to be quite reasonable from the physical point of view.

(2) With reference to his Figure 1, Bretschneider makes some effort to fit an $H \sim v^2$ curve to the observed data by breaking up his curve into two lines with different slopes. These two lines with two different slopes are supposed to fit the data for wind speeds less than 7 m/sec, a 'smooth zone' and for more than 7 m/sec a 'rough zone,' separately. Not only does this seem very artificial, but the concept of a critical wind speed was given up by its original promulgator, Munk, several years ago. Most oceanographers today will agree to the fact that the sea surface acts as a hydrodynamically rough surface not only at high but also at low wind speeds, as long as waves and especially steep ripples (cat paws) cover the surface.

(3) Another point where Bretschneider vigorously tries to force his belief into the observations is the neglect of the data at a wind speed of 3 m/sec. It is hard to understand why observations at low wind speeds have to be neglected for a derivation of a wave height-wind speed relationship, in order to be "in agreement with sound engineering practices." If one follows Bretschneider's curves for a 'smooth zone' the wave height at a wind speed of 1 m/sec (2 knots) at an anemometer height of 6 to 8 m should be 10 cm! This is obviously much too high for a pure wind-generated sea at a wind speed of two knots.

At this point we have to admit that at the ocean surface at a wind speed of two knots often higher 'waves' than the ripples are observed, due to the presence of a swell or a dead sea. On the other hand, at wind speeds of more than about 40 knots the duration of the wind is often not long enough to generate a fully arisen sea with maximum wave heights. Bretschneider with his purely empirical approach will most probably use data which show higher 'waves' at low wind speeds and lower 'waves' at high wind speeds due to the facts which have just been stated. With these data he will most likely tend to advocate the $H \sim v^3$ law.

(4) Another misinterpretation by Bretschneider is concerned with his interpretation of the work of Cox and Munk. He concludes that Neumann is uncertain as to the exact relationship for the power of v in the significant height of a fully developed sea on the basis of a quotation from Cox and Munk. He quotes from their work: "Neumann states that his data are convincingly better in accord with $T_T \sim T^4$ than T^3 or T^5." The T^4 referred to occurs in (3) along with a dT and it leads to the conclusion that the significant height varies according to a $v^{2.5}$ law. Thus there is no uncertainty as to the exact relationship. It does not necessarily follow that since $\bar{T}$, the average apparent period, is proportional to v, H is proportional to v^2 as Bretschneider has implied.

The v^2 law versus the $v^{2.5}$ law has created quite a controversy, and this review has added only a little more controversy. There are two proposed theoretical wave spectra now in existence which yield a v^2 law. Neither of these proposed spectra agrees with the results of project SWOP soon to be reported by *Chase* and others [1957] which verify the Neumann spectrum at one particular wind speed. For a review of the present status of ocean wave theory the new work by *Roll* [1957] makes many interesting comparisons. *Neumann* and *Pierson* [in preparation] are preparing a paper on the subject of wave spectra and wave forecasting methods which should be ready soon.

Since the publication of H. O. Pub. 603, we have continued our efforts either to improve or disprove the results contained therein. As of this date we are still of the opinion that it is the most nearly correct of all methods for forecasting waves. Only one minor modification in the methods of forecasting swell is needed due to the results of project SWOP.

There is only one way to resolve the controversies now in existence. It is to observe waves as precisely as possible either visually or by instrument, using a sound statistical method of data analysis, and test all theoretical formulas and curves against the observations before throwing away most of the value of the data by plotting it in dimensionless forms. For example, *Rattray* and *Burt* [1956] have tested both the SMB and the PNJ methods in a situation where the winds were 55 knots for 18 hr and the fetch was quite long. The result was a tie with respect to the significant height, and, in our opinion, with respect to the significant period (SMB) and average period (PNJ). Of course if the theoretical spectrum is correct much more information is contained in the PNJ method.

On the basis of the observations and data which went into the construction of the CCS curves, as confirmed for one particular case by the results of Rattray and Burt we recommend that both methods be used in all cases and compared wherever possible with observations. Just because the fully

developed sea is higher does not necessarily mean that the partially developed seas as a function of fetch and duration will differ by very much in the SMB and PNJ methods. If both methods are applied, then the forecaster can describe the results of the comparison in the scientific literature, form his own judgment as to the relative merits of the methods, and at the same time provide the scientific community with needed data on how well the methods work.

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Use of a Taylor Series as an Interpolation Formula with Magnetic Intensity Values

During the International Geophysical Year, in the exploration of the upper atmosphere, rockets and satellites equipped with proton precession magnetometers may be used to measure the scalar magnetic intensity at discrete points scattered throughout an appreciable volume of space. These data will be useful in determining the nature of the main geomagnetic field at high altitudes and the characteristics of the field of extra-terrestrial sources such as ring currents. In the analysis of the data it may be convenient to use, in place of a set of discrete measurements, an analytic representation of the scalar intensity that is valid over a large, continuous region of space. It is the purpose here to treat briefly the use of a Taylor series as an interpolation formula for the intensity.

In the regions external to sources of magnetism, the scalar magnetic intensity F has continuous derivatives and, therefore, can be expanded in a Taylor series. Using spherical polar coordinates with origin at Earth's center, the Taylor series in three dimensions can be written as

$$F(\theta, \lambda, r) = F(\theta_0, \lambda_0, r_0) + \left(\frac{\alpha\partial}{\partial\theta} + \frac{\beta\partial}{\partial\lambda} + \frac{\tau\partial}{\partial r}\right) F(\theta_0, \lambda_0, r_0) + \cdots \quad (1)$$

where θ, λ, and r are respectively the colatitude, east longitude, and radial distance from the center of the Earth; θ_0, λ_0, and r_0 are the coordinates of the point about which the expansion is made; $\alpha = \theta - \theta_0$; $\beta = \lambda - \lambda_0$; and $\tau = r - r_0$.

Equation (1) may be written as

$$F(\theta, \lambda, r) = F(\theta_0, \lambda_0, r_0) + a\alpha + b\beta + c\tau + \cdots \quad (2)$$

where

$$a = \partial F/\partial\theta; \qquad b = \partial F/\partial\lambda; \qquad c = \partial F/\partial r \quad (3)$$

and where the derivatives in (1) and (3) are evaluated at the point with coordinates θ_0, λ_0, and r_0.

In practice, one can compute with the measured data, say by a method of least squares, the coefficients in (2); the resulting series can be used to determine F at unmeasured points. By this means a continuous representation of the intensity may be obtained throughout a relatively large volume of space. Since the rapidity of convergence of the series depends on the type of field and the volume interval over which the interpolation is made, there will be a variation in the number of terms required in the finite series. However, the minimum number of required terms may be determined from considerations with the Earth's dipole field, and a calculation was made with this field in a region containing possible orbits of the Vanguard satellite.

The field of the Earth's dipole is given in spherical harmonics by

$$F = 31{,}200(a/r)^3(1 + 3\cos^2\theta)^{\frac{1}{2}}\text{ gamma} \quad (4)$$

where the numerical coefficient is that determined in harmonic analysis by *Vestine* and others [1947]; a is the radius of the Earth, about 3960 miles, and one gamma equals 10^{-5} cgs unit.

TABLE 1 – *Computed values of intensity of dipole field: intensity values in gammas*

Colatitude of interpolated point[a]	Computed value	
	With a Taylor series of ten terms	With the harmonic of Eq. (4)
65	25,322	25,324
75	22,394	22,393
85	20,670	20,666
95	20,661	20,666
105	22,388	22,393
115	25,320	25,324

[a] The altitude of each interpolated point is 600 miles.

It was assumed that the volume containing the satellite measurements could be divided into an interval of space where the altitude above the surface of the Earth varied between 200 and 600 miles and where the colatitude varied by ten degrees. Since the intensity in (4) is independent of longitude, the λ-variation in the Taylor series may be neglected. Through the following procedure a separate Taylor series was formed for the intensity F in each such interval in the range of colatitude.

Performing the differentiation required in (1) or (3) on (4), one obtains the coefficients in the Taylor series which in this case was an expansion around the central point in the space element. The Taylor series is then used in determining the intensity at a peripheral point. For example, with regard to Table 1, for the interpolated point with $\theta = 65°$ and altitude 600 miles, the expansion was made about the point with $\theta_0 = 60°$ and altitude 400 miles; for the interpolated point with $\theta = 75°$ and altitude 600 miles, the expansion was made around the point with $\theta_0 = 70°$ and altitude 400 miles.

The results shown in Table 1 indicate that a finite series of ten terms will adequately describe the intensity of the dipole field in a region of space where the range of r and θ is 400 miles and ten degrees, respectively. Additional terms will be required if a larger space element is treated or if the non-dipole contributions are significant at the satellite altitudes. Since the number of required terms is also the minimum number of required measurements, at least ten satellite measurements will be required in each interval herein treated.

The Taylor series can also be used with the total intensity magnetic anomalies treated in geophysical prospecting.

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REMARKS ON THE ANALYTICAL DERIVATION OF THE DARCY EQUATION

In making these remarks on Warren A. Hall's paper, "An analytical derivation of the Darcy equation" [*Trans.*, **37**, 185–188], I should like to begin by acknowledging my debt to him for having first interested me in this question during a conversation we had in the summer of 1954. On that occasion he showed me a draft of his paper, and I have been giving some thought to these matters from time to time since then. Hall recognizes the shakiness of the present theoretical foundations of Darcy's law, and, indeed, of flow studies in porous materials in general. This is all too often glossed over, sometimes at the expense of physical insight.

Essentially, Hall derives the Stokes-Navier equation for the steady state under the restriction that inertia forces are negligible and applies it to porous media by assuming a uniform distribution of solid surface within all fluid elements. The approach implies the additional assumption that the shear stress per unit of solid surface area is constant; this assumption seems drastic enough to warrant explicit recognition.

The present writer has found that results for saturated media similar to Hall's follow with greater generality and less labor directly from the Stokes-Navier equation. It is hoped to submit for publication shortly work along these lines in which the relationship between Darcy's law and classical hydrodynamics is explored and leads to means for computing permeability from medium geometry.

It is clearly impossible to dispose of these larger issues in this short note, and it seems profitable

to confine attention to the matter of Hall's extension of his analysis to unsaturated systems. This is sufficiently independent of these other questions to remain amenable to discussion. I do not follow Hall's argument on this point with any certainty, but I cannot find in his paper any recognition of the shear stress at the interface between the fluid phases. Admittedly, this will usually be small in liquid-gas systems, because of the relatively small pressure gradients in the gas phase; but any formal extension of Darcy's law to an unsaturated (or two-phase) system must rely on the postulate that the drag between the phases is negligibly small.

Perhaps I may be permitted to stray slightly from the liquid-gas system and remark on two-phase fluid flow in porous media in general, that is, including those cases where the viscosities (and pressure gradients) in the two phases are comparable in magnitude. Here, of course, the physical principles remain the same as in the liquid-gas case, but the 'negligible drag' postulate cannot be supported by the previous argument. There is at least some evidence from petroleum engineering research that, even in this case, the extension of Darcy's law may still hold fairly well. It has been suggested that the drag is still small here because the phases tend to be segregated into separate channels, so that the contact area between them is relatively small.

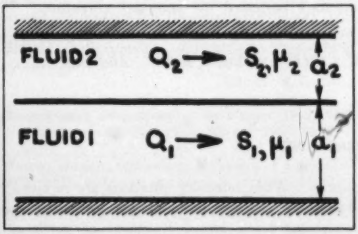

FIG. 1 – Two-phase laminar linear-flow system

The effect of drag between the phases may be illustrated very simply by considering the two-phase laminar linear flow system depicted in Figure 1. Fluid 1 is in contact with the lower plane solid surface, fluid 2 with the upper one; the interface between the fluids is a third plane. The three planes are parallel, with the interface at distance a_1 from the lower solid surface and at distance a_2 from the upper one. The viscosities are denoted by μ, the pressure gradients by s; the total discharge for each phase per unit width of the system by Q. Suffixes 1, 2 denote values for fluids 1, 2 respectively.

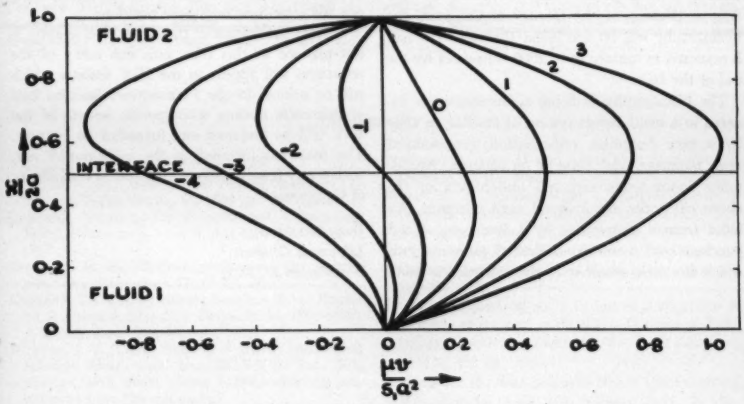

FIG. 2 — Velocity profiles in system of Figure 1 for $\mu_1 = \mu_2 = \mu$, $a_1 = a_2 = a$; v denotes velocity, positive in the sense opposite to s positive; x denotes distance from the lower solid surface; number on each curve denotes value of s_2/s_1

Equating shear stresses and velocities in the two phases at the interface, we obtain

$$Q_1 = -\frac{s_1 a_1^3}{12\mu_1}\left(\frac{4\mu_1 a_2 + \mu_2 a_1}{\mu_1 a_2 + \mu_2 a_1}\right) - \frac{s_2 a_2^3 a_1^2}{4(\mu_1 a_2 + \mu_2 a_1)} \quad (1)$$

with a similar expression for Q_2. It is evident that, in general, the flow in each phase is influenced by the pressure gradient in the other phase. For $a_1 = a_2 = a$, (1) reduces to

$$Q_1 = -\frac{a^2}{4(\mu_1 + \mu_2)}\left[s_1\left(\frac{4}{3} + \frac{1}{3}\frac{\mu_2}{\mu_1}\right) + s_2\right] \quad (2)$$

The relative importance of s_2 in determining Q_1 increases as μ_2/μ_1 decreases; any tendency for the influence of fluid 2 on the flow of fluid 1 to decrease as μ_2/μ_1 decreases is due not to the small viscosity of fluid 2 *per se*, but to the consequent small value of s_2.

For $a_1 = a_2$, $\mu_1 = \mu_2$, the relative magnitudes of the influences on Q_1 of s_1 and s_2 are in the ratio 5:3.

Figure 2 shows the variation of the velocity profile in the two fluids when s_2/s_1 is allowed to vary between $+3$ and -4 for the case $a_1 = a_2 = a$, $\mu_1 = \mu_2 = \mu$. The profound influence of s_2 on the velocity profile in fluid 1 will be evident.

In this example, the geometry has been simplified so that the hydrodynamic relationships might be shown easily. It is recognized that, in any real medium, the differences in pressure gradient across the interface could be sustained only if the interface possessed the necessary curvature

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AN IGY BIBLIOGRAPHY

A new bibliography of the technical and some of the popular literature on the International Geophysical Year will be of interest to members of the American Geophysical Union. One of several continuing bibliographies being prepared in the Science Division of the Library of Congress, the bibliography will be continued through 1958 and is expected to contain over 2000 references by the end of the IGY.

The bibliography is being comprehensively indexed in a multi-aspect system of the Batten type by science discipline, organization, geographical area, language, and type of publication. Appropriate index terms arranged under each of the above categories are assigned each reference. An index term is represented by a Remington-Rand punched card with 500 dedicated positions into which the serial number of the reference is hand punched. When reference questions are received, appropriate subject headings are generated by combining index terms. Retrieval of pertinent references for the inquiry is accomplished by superimposing the selected punched cards and reading out the coincident numbered positions.

Formal publication of the entire bibliography is not planned at this time, although many of the references will appear in the IGY *Bulletin* which will be printed in the *Transactions*. Selected lists of references dealing with specific aspects of the IGY will be prepared and furnished on request. The materials included in the bibliography are, with a very few exceptions, available in the Library of Congress.

JOHN SHERROD
Library of Congress, Washington 25, D. C.

Reviews, Abstracts, and Bibliography

Reviews and Abstracts

MURDOCH, JOSEPH, AND ROBERT W. WEBB, *Minerals of California*, Calif., Dept. of Natural Res. Div. of Mines, Bul. 173, Dec. 1956, 452 pp. + 3 colored plates, $3.00.

Minerals of California is the eighth catalog of mineral species found within the state. This catalog brings the number of California species up to 523. The minerals are arranged alphabetically. The properties of each species are briefly summarized. The greatest amount of space is devoted to a description of the localities and to the manner of occurrence. The preparation of this part of the book required a considerable amount of time, particularly in the verification of the records. In documenting the records the authors compiled a very complete bibliography (pp. 355–452). This bulletin is an outstanding contribution to topographical mineralogy.

GEORGE T. FAUST

Oceanographic Observations of the Pacific: 1949, University of California Press, 363 pp., 1957; $4.50.

Edited by Norris Rakestraw, Paul Horrer, and Warren Wooster, this volume is the first of a projected series which will serve as a medium for the publication of oceanographic serial station data from the Pacific. The volume for 1949 contains observations made by the U. S. Navy Electronics Laboratory, San Diego; Scripps Institution of Oceanography, La Jolla; and the Pacific Oceanic Fisheries Investigations of the Fish and Wildlife Service, Honolulu. The vessels involved were the U.S.S. *Serrano*, R/V's *Horizon* and *Crest*, U.S.F.&W.L.S. vessels *Black Douglas* and *Hugh M. Smith*, and the Calif. F.&G. vessel *N. B. Scofield*. Illustrations showing the station positions are provided, as well as charts (by 5° quadrangles) of all bathythermograms on file at Scripps Institution for the period 1941–1949.

A bibliography is also furnished, listing published papers based on the data, but not the reports in which preliminary versions of the observations appeared.

The data are presented both as observed values of depth, temperature, salinity, and oxygen and phosphate (when determined) and as interpolated values at standard depths, with computed density, specific volume anomaly, and dynamic depth.

There is a slight error on page 14 in the definition of σ_t, in which the quantity ρ is stated to be density in g/cm³, whereas it actually is specific gravity in g/ml. The column headings correctly give σ_t as g/L. The quantity δ, although found by subtracting the reciprocals of two specific gravities, is numerically equal (to four significant figures) to the difference of the reciprocals of the corresponding densities, so that it is conveniently called specific volume anomaly and given the units of cm³/g.

The book is stoutly bound and handsomely printed, by the process used for the pre-1956 *Transactions* (except that the right margins are justified). Since oceanographic literature commonly cites individual stations by ship name, station number, and date, an index of this nature would be a welcome addition to future volumes. Any reduction in the seven-year lag between observations and publication would also be welcomed.

J. L.

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Notes and Personalia

Notes

NINTH PACIFIC SCIENCE CONGRESS—The Ninth Pacific Science Congress will be held in Bangkok, Thailand, November 18–30, 1957, with tours in the period following continuing through the 9th of December. Interested persons should get into touch with the Secretary of the Congress, Dr. Charng Ratanarat, Department of Science, Ministry of Industry, Rama VI Road, Bangkok, Thailand, or in the case of citizens of the United States, get into touch with Mr. Harold J. Coolidge, 2101 Constitution Avenue, Washington 25, D. C.

ANNALS OF THE INTERNATIONAL GEOPHYSICAL YEAR—The International Committee for the International Geophysical Year (CSAGI) has arranged with Pergamon Press for the publication of the *Annals of the International Geophysical Year* under the general editorship of Harold Spencer Jones which will record the history, organization, programs, and methods of this international activity. Subscription rates are $17.00 per volume, with six volumes estimated to be about 400 pages each to be published during 1957 and 1958. Orders should be placed with the Pergamon Press, 122 East 55th Street, New York 22, New York.

GRADUATE ASSISTANTSHIPS IN METEOROLOGY AT FLORIDA STATE UNIVERSITY—Announcement has been made of availability of graduate assistantships for

1958–1959 for candidates for master's and doctor's degrees in meteorology. No previous meteorological education is necessary, but calculus and university-level physics are requirements. The stipend for candidates holding a bachelor's degree is $1800 and for those with a master's degree, $2100. The student is permitted to carry ten semester hours of course work. Out-of-state tuition is waived, but resident fees of about $75 per semester are assessed. Further information and application forms may be secured from Werner A. Baum, Department of Meteorology, Florida State University, Tallahassee, Florida.

COASTAL ENGINEERING CONFERENCE—The Sixth International Conference on Coastal Engineering will be held at the University of Florida in Gainesville, December 2–7, 1957. Persons interested in this should get into touch with Dr. Per Bruun, Coastal Engineering Laboratory, University of Florida, Gainesville, Florida.

SYMPOSIUM ON ATMOSPHERIC DIFFUSION AND AIR-POLLUTION—Plans are being made for an international symposium on atmospheric diffusion and air pollution to be held in Oxford, England, August 24–29, 1958. Persons in the United States should get into touch with F. N. Frenkiel, Applied Physics Laboratory, Johns Hopkins University, Silver Spring, Maryland.

EXPERIMENT IN THE CONTROL OF FOREST FIRES—Foresters and meteorologists in the northern mountain states of Montana and Idaho are exploring the possibilities of controlling thunder storms in order to eliminate the ravages of forest fires caused by lightning. The work includes the seeding of thunderheads during the upward growth of cumulus clouds before lightning is produced. The records show that 100,000 forest fires were caused by lightning between 1940 and 1955 in the 12 western states.

STUDY OF ARID PROBLEMS IN PERU—A UNESCO group is working on Peru's arid zone problems in connection with the Arid Zone Institute of Peru. This group is studying the characteristics of soils in the Peruvian coastal desert and the plants that manage to survive there. The group has recently been joined by Knud Rahn, a Danish student of South American climatological problems, who is Secretary of the Danish Conservation Society.

WORK OF THE ARCTIC INSTITUTE—In 1957 the field research program of the Arctic Institute has been undertaken with the aid of 37 grants-in-aid as against 31 in 1956. The Earth sciences are represented by ten of the projects, including a continuation of the long-range climatological studies and studies of soil-formation processes. One of the bases for the operation of the work is the Arctic Research Laboratory of the Office of Naval Research at Point Barrow, Alaska. The program receives support from the Office of Naval Research, the Canadian Government, the Sir Frederick Banting Fund, and private individuals and industrial concerns, both in Canada and the United States.

PROGRAMS ON THE BELL SYSTEM SCIENCE SERIES—It has been announced by the Bell Telephone Laboratories and affiliates that the following television programs on science are to be presented over the NBC network:

"The Strange Case of the Cosmic Rays," October 25, 21h to 22h EDT

"Our Mr. Sun," December 15, 1957, 17h 30m to 18h 30m, EST

"The Unchained Goddess," February 12, 1958, 21h to 22h, EST

"Hemo the Magnificient" (story of blood), March 16, 1958, 17h 30m to 18h 30m, EST

The programs relating to the Sun and to blood were originally broadcast during the past year over the Columbia Broadcasting System. The films are in color and, although oriented to the lay public, each has a substantial panel of advisors to keep the stories on scientifically sound principles.

GEOGRAPHICAL FIELD RESEARCH IN FOREIGN AREAS—The National Academy of Sciences—National Research Council will conduct in 1958, under the financial sponsorship of the Office of Naval Research, its third annual program of geographical field research in foreign areas. The objective of the program is to strengthen American geography by stimulating greater participation by young Americans in field research in areas outside of the United States. Support will be made available not only to young geographers but also to young scientists in related fields, such as geomorphology, climatology, ecology, and pedology. The extent of financial assistance will vary according to the needs involved. Applications for support of field work to be initiated before April 1, 1959 must be submitted prior to December 1, 1957 to Foreign Field Research Program, Division of Earth Sciences, 2101 Constitution Ave., Washington 25, D. C.

FIRST NATIONAL CONFERENCE ON APPLIED METEOROLOGY—The First National Conference on Applied Meteorology, to be held October 28–29, 1957, in Hartford, Connecticut, will bring together members of the meteorological profession and business and industry to discuss the effective application of weather information in business and industrial operations. For further information, write to Robert G. Miller, Weather Research Center, Travelers Insurance Companies, Hartford, Conn.

MEETING OF THE IUGG IN TORONTO—The Eleventh General Assembly of the International Union of Geodesy and Geophysics was held in Toronto, September 3–14, 1957, in accordance with the schedule. About 50 nations sent delegates and much of scientific value was presented in papers. The new officers of the Union are: President, J. Tuzo Wilson of the University of Toronto; Vice Presidents, V. V. Beloussov of the Academy of Sciences of the USSR and W. A. Heiskanen of the Finnish Geodetic Institute and the Institute of Geodesy and Photogrammetry of the Ohio State University. Georges A. Laclavere was re-elected General Secretary. Among the Association officers elected were Joseph Kaplan as President of the Association of Geomagnetism and Aeronomy and H. G. Wilm as President of the Association of Hydrology. Finland has been selected as the place of the Twelfth General Assembly to be held July 25–August 8, 1960.

A more complete report will appear in the December issue of the *Transactions*.

NEW SUBMARINE MOUNTAIN RANGE—A team of geophysicists from the Lamont Geological Observatory of Columbia University has discovered a new undersea mountain range north of Point Barrow. This group is on a floating ice pack under the leadership of Maurice J. Davidson in connection with the work of the International Geophysical Year. Their radio report indicates that this major submarine range parallels the great Lamonosov Ridge in the central Arctic. Depths off the range are of the order of 10,000 ft but over the range there is less than 5000 ft, indicating the range to extend 5000 ft above the ocean floor at 83° 51.5′ north and 168° 43′ west.

Personalia

WILLIAM MANSFIELD ADAMS has recently returned from a year's study at the Istituto di Fisica Terrestre, Universita di Napoli, on a Fulbright Fellowship, and has taken up duties with the Geotechnical Corporation, Dallas, Texas.

L. V. BERKNER, President of Associated Universities, Inc., and Vice President of the American Geophysical Union, was elected President of the Union Radio Scientifique Internationale (URSI) at the XIIth General Assembly recently held in Boulder, Colorado.

KENNETH E. BULLEN of the Department of Applied Mathematics of the University of Sydney, Chairman of the Australian National Committee for the International Geophysical Year and retiring President of the Association of Seismology and Physics of the Earth's Interior of the International Union of Geodesy and Geophysics, was designated as a speaker for the Distinguished Lectures Committee of the Society of Exploration Geophysicists and spoke at various centers in the United States and Canada during September and October 1957. He also spoke at the Mathematical Physics Section of the National Bureau of Standards on September 27 on the subject "Seismology and the Earth's Interior."

JOHN H. CONOVER has been appointed to succeed Charles F. Brooks as Director of the Blue Hill Meteorological Observatory of Harvard University.

GEORGE B. CRESSEY, Professor of Geography at Syracuse University, will spend the academic year 1957–58 at the University of Beirut in Lebanon under a Smith-Mundt grant.

PAUL E. DAMON, Research Associate at Lamont Geological Observatory of Columbia University, has taken up duties as Associate Professor of Geology at the University of Arizona.

RICHARD M. FOOSE has left his work as Chairman of the Geology Department at Franklin and Marshall College for a new position as Head of the newly formed Earth Sciences Department, Physical Sciences Division of the Stanford Research Institute.

GEORGE GAMOW, Professor of Physics at the University of Colorado, recently gave the sixth annual Edsel B. Ford Lecture in the auditorium of the Henry Ford Hospital in Detroit on the subject of molecular genetics.

GEORGE R. GRANTHAM has taken up duties as branch office manager of the Benham Engineering Company in Muskogee, Oklahoma.

FLOYD W. HOUGH, who has recently retired as Chief of the Geodetic Division of the U. S. Army Map Service, has opened a consulting office in geodesy and geodetic engineering in Washington, D. C.

JOSEPH KAPLAN, Professor of Physics at the University of California, was recently awarded an honorary doctorate from Carleton College and another from Notre Dame University.

DON KIRKHAM, Professor of Soils and Physics at Iowa State College, is now in Belgium on a Guggenheim fellowship for research and a Fulbright award for lecturing in soil physics at the State Agricultural University, Ghent, Belgium. W. R. Van Wijk, Head of the Institute of Physics and Meteorology, University of Wageningen, will take Kirkham's place while he is abroad.

PAUL LIEBER, Professor of Geophysics of Rensselaer Polytechnic Institute on leave from the University of California at Berkeley, has received a Fulbright Lectureship and left early in October to do research at the Technion in Haifa, Israel.

WALTER C. LOWDERMILK, Past President of the American Geophysical Union, has returned from an assignment with the Food and Agricultural Organization of the United Nations to Israel where he has spent the last three years at the Israel Institute of Technology developing courses in agricultural engineering and serving as consultant on soil and water conservation problems to the government of Israel. On his return trip he devoted several weeks to water and conservation problems in Yugoslavia under an FAO assignment. He plans to return to Israel in February 1958 in connection with the cornerstone laying of a new building of agricultural engineering.

JOHN S. MCNOWN has resigned his position as Professor of Engineering Mechanics at the University of Michigan to become Dean of the School of Engineering and Architecture and Professor of Applied Mechanics at the University of Kansas.

CHARLES B. OFFICER, Associate Professor of Rice Institute, has left his work and taken up new duties with the Gravity Meter Exploration Company, GMX Corporation, Geophysical Associates International, with headquarters in Houston, Texas.

ERNEST J. PARKIN has left his duties with the U. S. Coast and Geodetic Survey and taken up work with the Air Photographic and Charting Service at the Air Force Base, Orlando, Florida.

AUBREY L. SHARP has taken up duties as Supervisory Hydrologist with the Agricultural Research Service at Lincoln, Nebraska, to head up a work group to study hydrologic problems of the Great Plains in cooperation with the Soil Conservation Service and the U. S. Bureau of Reclamation.

THORNDIKE SAVILLE, has recently been designated Dean Emeritus at New York University and has established an office as a consulting hydraulic and sanitary engineer. He will maintain his address at New York University, University Heights, New York 53, N. Y. and also Riverdale-on-Hudson, New York, N. Y.

VICTOR VACQUIER, until recently engaged in work with the New Mexico Institute of Mining and Technology, has taken up duties with the Marine Physical Laboratory at the University of California in San Diego.

STEPHEN S. VISHER, long Professor of Geography at Indiana University, and widely known for his works on climate, has been appointed Research Professor at Indiana University.

ROBERT WARREN KELLOGG died April 13, 1956, at the age of 53. He was born at Sisterville, West Virginia, and took his baccalaureate degree at Kansas State College in 1932. After about ten or twelve years of diverse experience he entered on duty with the U. S. Geological Survey in 1945, where he continued until his passing. He became a member of AGU in 1947.

HANS KRAMER, Brigadier General, U. S. Army (retired), and Consulting Engineer of San Francisco, died February 16, 1957, at the age of 63. He was born in Magdeburg, Germany, and entered his collegiate career at the University of Michigan, subsequently entering the U. S. Military Academy, from which he graduated in 1918. He took his master's degree from the University of Pennsylvania in 1928, and as a Freeman Scholar took his doctorate at the University of Dresden in 1932. His service in the Army until his retirement in 1945 included a number of major engineering assignments, among them the Conchas Dam in New Mexico and work on the Panama Canal. He had been a member of AGU since 1932.

ARTHUR A. LANE of the U. S. Weather Bureau with headquarters in Louisville, Kentucky, died June 17, 1957, at the age of 51. He was born at Lynn, Massachusetts, and pursued studies at Massachusetts Agricultural College and the U. S. Naval Academy. In 1936, he entered the service of the U. S. Weather Bureau in Albany and worked at various stations, having been assigned as Meteorologist in Charge at the Naval Station in 1944. He had been a member of AGU since 1950.

IRVING LANGMUIR, Nobel Prize winner in chemistry and consultant for the General Electric Company, died August 16, 1957, at Falmouth on Cape Cod at the age of 76. He was born in Brooklyn, New York. He took his baccalaureate degree from Columbia University in 1903 and his doctorate from the University of Goettingen, Germany, in 1906, and received honorary doctorates from Columbia, Princeton, Harvard, Johns Hopkins, and several other colleges and universities. He entered on duty in 1906 as Research Chemist and Geophysicist with General Electric, becoming Assistant Director of the Research Laboratories in 1909 and Associate Director in 1932. He retired in 1950, continuing with the company on a consulting basis. He was winner of numerous awards, perhaps the most outstanding of which was the Nobel Prize in chemistry in 1932. His interests ranged over a very broad field having in general their roots in chemistry which led him into the problems of cloud physics and nucleation and the inducing of artificial rainfall. He had been a member of AGU since 1948.

CARL-GUSTAV ROSSBY, Professor of the University of Stockholm, and Director of the Stockholm Meteorological Institute, died in Stockholm, August 19, 1957, at the age of 59. He was born in Stockholm and took his baccalaureate degree in Stockholm in 1918 and his master of science degree in 1925. He attended the Geophysical Institute in Bergen in 1919 and 1920; the Geophysical Institute in Leipzig in 1920. He held an honorary doctorate from Kenyon College. He entered the Norwegian Meteorological Service in 1919 and then the Swedish Service in 1922, where he continued until 1925. In 1926, he was a Swedish-American Foundation fellow and subsequently did work under the Guggenheim Foundation for the Promotion of Aeronautics from 1927 to 1928. He taught at the Massachusetts Institute of Technology from 1928 to 1941, and from 1939 to 1941 was Assistant Chief in Charge of Research of the U. S. Weather Bureau. He took up duties as Professor of Meteorology at the University of Chicago, where he continued until 1951. He had been a Research Associate in Oceanography at Woods Hole Oceanographic Institution since 1932. He was instrumental in the development of the Meteorological Institute in Sweden in which he became a professor in 1947. He was the recipient of many honors and awards and only a few months ago was the subject of a cover article in *Time* magazine, noting his outstanding accomplishments in meteorology and oceanography. He had been a member of AGU since 1932.

HARALD ULRIK SVERDRUP, one of the world's leading geophysicists working especially in the fields of oceanography and meteorology, died in Oslo, Norway, August 20, 1957 at the of 69. He was born in Sogndal, Norway. He took his baccalaureate degree from the University of Oslo in 1911, his master's degree in 1914, and his doctorate in 1917, all from the University of Oslo. He held an honorary degree from the University of California. In the early days of his professional career, he worked with V. Bjerknes. From 1917 to 1925 he was in charge of the scientific work on the *Maud* Expedition in the Arctic. He became a Research Associate at the Carnegie Institution of Washington in 1926 and was Professor of Meteorology at the Geophysical Institute of Bergen from 1926 to 1930. In 1931 he was in charge of the scientific work for the Wilkins-Ellsworth Submarine Arctic Expedition on board the *Nautilus*. In 1936 he came to the United States, became a citizen, and was Director of Scripps Institution of

Oceanography from 1936 to 1947. He was recalled to Norway to take up duties at the North Polar Institute in Oslo, where he continued until the time of his death. He was Vice President of the American Geophysical Union in 1947 and 1948, and was named the thirteenth recipient of the William Bowie Medal in 1951. He was also the recipient of many international honors and awards for his outstanding work. He had been a member of AGU since 1936.

GEORGE W. TRAUGER of Lindsay, California, died June 1, 1957, at the age of 78. He was born at Trauger, Pennsylvania. He took his baccalaureate degree from Indiana State College, Indiana, Pennsylvania, in 1901. From 1901 to 1907 he worked with the West Pennsylvania Railroad and Wilkins Engineering Company. In 1907 he went to Minnesota, where he taught for a while and worked with the County and City Engineers of Glenwood, Minnesota. In 1915, he moved to California, where he helped design and build the Lindsay Strathmore Irrigation Works which he continued to manage until 1950 when he retired, continuing as a consultant up to the time of his death. He was a member of AGU from 1947 to 1954.

Special Announcements

MEETING OF PACIFIC NORTHWEST REGIONAL GROUP—The annual fall meeting of the Pacific Northwest Regional Group will be held in Pullman, Washington, October 30–31, 1957. Norbert Leupold (P. O. Box 5082, Portland 13, Ore.) is Chairman of the Branch for the current year with Franklin I. Badgley (Department of Meteorology, University of Washington, Seattle 5, Wash.) Secretary-Treasurer. The Program Chairman for the meeting in Pullman is T. H. Campbell (Civil Engineering Department, University of Washington, Seattle 5, Wash.). Although it is perhaps too late to be included in the program, this last-minute notice may call the attention of some who desire to attend the meeting.

PACIFIC SOUTHWEST REGIONAL MEETING IN PASADENA, FEBRUARY 6–7, 1958—Plans are progressing rapidly for the meeting and the request is made that titles with abstracts of not more than 200 words should be provided in triplicate not later than December 1, 1957. Send communications concerning the program to Dr. Norman H. Brooks, California Institute of Technology, Pasadena, California. Papers are especially invited in meteorology, hydrology, and oceanography and their interrelationships, and those relating to other phases of geophysics will be placed in a special session or general session as the number may dictate. In preparing abstracts, please follow the instructions set forth in Suggestions to Authors published in the April 1957 issue, pages 284–286. The Chairman of the Regional Committee is Vito A. Vanoni of California Institute of Technology, and others on the program committee are Eugene Bollay of Northam Electronics, Inc., 2420 North Lake Avenue, Altadena, California, and Townsend Cromwell, Sr., of Scripps Institution of Oceanography at La Jolla.

THIRTY-NINTH ANNUAL MEETING TO BE HELD IN WASHINGTON, D. C., MAY 5–7, 1958—As announced in the August issue of the *Transactions*, the Thirty-Ninth Annual Meeting will be held in Washington, D. C., Monday to Wednesday, May 5–7, 1958. The plans of the various Sections are now getting under way, and it is anticipated that all Sections will have meetings. There will also be general meetings of the Union as a whole, including a Smoker on Monday evening, May 5, a general evening session including Award of the William Bowie Medal on Tuesday evening, and a general session on Wednesday afternoon. Suggestions with respect to any of the Section or Union meetings are invited. Suggestions for the Union meeting should be sent to P. H. Abelson, Chairman of the Committee on Meetings, AGU, 2801 Upton Street, N.W., Washington 8, D. C. With respect to Section meetings, see list of Secretaries and Program Chairmen below.

This announcement will also serve as an invitation for members and others to send word of plans for papers to be presented. Titles of papers with three copies of the abstracts should be sent in as soon as possible and not later than March 5, 1958. Please also give information concerning the time required (most papers are allowed from 10 to 20 minutes) and the projection equipment needed. This word should be sent to the office of AGU at 1515 Massachusetts Avenue, N.W., Washington 5, D. C., or to the Secretary or Program Chairman of the appropriate Section, as follows:

Geodesy, Frank L. Culley, Army Map Service, 6500 Brooks Lane, Washington 25, D. C., or Donald A. Rice (Program Chairman), U. S. Coast and Geodetic Survey, Washington 25, D. C.

Seismology, James A. Peoples, Jr., 39 Edgewater Drive, Waltham 54, Massachusetts.

Meteorology, Woodrow C. Jacobs, 3812 Nash Street, S.E., Washington 20, D. C.

Terrestrial Magnetism and Electricity, Robert E. Gebhardt, U. S. Coast and Geodetic Survey, Corbin, Virginia.

Oceanography, Donald W. Pritchard, Johns Hopkins University, Baltimore 18, Maryland.

Volcanology, Geochemistry, and Petrology, Lyman T. Aldrich, Department of Terrestrial Magnetism, 5241 Broad Branch Road, N.W., Washington 15, D. C.

Hydrology, Ralph N. Wilson, 3322 Stanford Street, University Hills, Hyattsville, Maryland, or Bernard Frank (Program Chairman), 2807 Washington Avenue, Chevy Chase 15, Maryland.

Tectonophysics, Benjamin F. Howell, Jr., Dept. of Geophysics and Geochemistry, Pennsylvania State University, University Park, Pennsylvania.

As Section Secretaries reserve the right to close filled programs in advance of the dates indicated, please make it a point to send word in early. Abstracts of the papers are published in the program. Remember that an abstract is an opportunity to bring the important results of your work to all those that see the program. The abstract should be concise but comprehensive and informative, and must not exceed 200 words. Longer abstracts will be reduced to 200 words or omitted at the editor's discretion. Complete manuscripts are not necessary but are desired and should be forwarded to the office of the Union by April 15 in order to be available for science news writers. Please indicate whether the paper is being submitted for the program only or also for consideration for publication in the *Transactions*. If a paper is written in collaboration, please indicate by whom it will be presented. Arrangements can usually be made with the Section Secretary or Program Chairman for the presentation of papers by authors who are unable to attend, but papers to be presented by title only are not included in the program.

Make hotel or room arrangements directly with the hotel of your choice at an early date. If you fail on the first attempt, bear in mind that advance bookings that are not taken up are cancelled two weeks in advance and that a follow-up request in mid-April may bring the desired response. We are making block bookings at three hotels again; an announcement regarding these will appear in the Special Announcements in the December issue of the *Transactions*.

NOTE TO ASSOCIATE MEMBERS—If your address bears the symbols A.M., this indicates that you are now recorded as an Associate Member in our membership rolls. A number of these have been of some years standing, and if these individuals have been actively engaged in some phase of the broad field of geophysics or closely related science, they are now eligible for full membership if total experience beyond the baccalaureate degree is at least three years. The initiative to change, however, is up to the individual. The application form published from time to time in issues of the *Transactions* may be adapted to make application for change of grade.

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IGY BULLETIN

A monthly survey by the U. S. National Committee for the International Geophysical Year. Established by and part of the National Academy of Sciences, the Committee is responsible for the U. S. International Geophysical Year program in which several hundred American scientists are participating and many public and private institutions are cooperating.

Status Report: The Upper Atmosphere Program

STUDIES during the IGY in five closely interrelated areas of scientific inquiry will contribute directly to a better understanding of high atmosphere conditions, behavior, and influence upon man's more immediate environment. Knowledge gained from investigations in any one of the disciplines of solar activity, cosmic rays, geomagnetism, ionospheric physics, and aurora and airglow can often be applied directly to explain phenomena in one or more of the others.

The influence of the sun in the high atmosphere is of central importance. Radiation from the quiet sun is responsible for the ionospheric layers and controls many chemical processes in the upper atmosphere. Disturbed solar conditions, however, directly affect radio communication via the ionosphere, and often cause unusual auroral, geomagnetic, and cosmic ray activity.

In this issue of the *Bulletin*, one section is devoted to the US-IGY program in each of the upper atmosphere disciplines, and there is a final section which reviews related experiments in the rocketry program.

The section on solar activity includes reports on the status of flare patrol projects, coronal observations, and mapping of the sun's magnetic fields.

The cosmic ray section reports the status of projects directed at the study of cosmic ray intensity, charge, and mass, including extensive high altitude balloon experiments. Preliminary findings are described.

The report on the geomagnetism program covers projects concerned with the recording of magnetic storm effects, measurement of space gradients of magnetic field disturbances, any relationships between meteorological and geomagnetic effects, studies of the postulated equatorial and northern geomagnetic upper atmosphere currents, recording of the fine detail of magnetic fluctuations, as well as widespread absolute measurements of the earth's field.

In ionospheric physics, the report describes IGY work in vertical incidence soundings, radio noise, ionospheric drifts, absorption, back scatter, sporadic E ionization, forward scatter and whistlers.

The section on aurora and airglow reports the status of programs utilizing the all-sky camera, volunteer visual observation, the use of patrol spectrographs and scanning spectrometers, the measurement of ionospheric absorption in auroral zones, and the recording of airglow intensity and spectral distribution.

The final section contains a summary report of preliminary experiment results of upper atmosphere probing by rockets.

Solar Activity Program

Variations of the sun's activity have been known from the earliest years of application of the telescope. Galileo's sunspot drawings made in 1612 are comparable in quality with drawings made today with small modern telescopes. A vast number of phenomena of the sun, in addition to sunspots, evince variations of one time scale or another.

No one today disputes that certain of the sun's changes are directly related to responses found in the earth's atmosphere. There are also many other suspected sun-earth relationships, the existence or importance of which is the subject of considerable discussion.

For the purposes of the IGY, there are three principal goals to be served by solar astronomers in their study of the sun's activity. They seek (1) to warn of the times of expected geophysical effects of solar activity; (2) to make comprehensive physical measurements of all possible solar phenomena accessible to their observing instruments; and (3) to use the observations of these phenomena, making appeal to theoretical knowledge, to provide a complete post-event assessment of the time variations of the invisible forms of solar emission, many of which, though not directly accessible to measurement, may be expected to have important geophysical effects.

The US-IGY program in solar activity involves the principal solar observatories of the country, plus one newcomer established on a modest scale in Hawaii for the purpose of filling the observational gap in the vast Pacific area. There are now ten sites where special solar observations are being conducted, with important volunteer observations also being made.

Solar flares are probably the most important of all solar phenomena that have well-known effects on the earth, although it should be kept in mind that flares are only one of about ten different solar phenomena which are being carefully observed and reported. As part of the International Flare Patrol, observations at intervals of three minutes or less are being taken at the Naval Research Laboratory (NRL), McMath-Hulbert Observatory, High Altitude Observatory, Sacramento Peak Observatory, Mount Wilson Observatory, and the University of Hawaii Solar Observatory. Two stations are awaiting delivery of high quality Lyot-designed flare patrol instruments built in France; these use birefringent filters of 0.75 A band pass. Three stations are using less elaborate instruments of smaller aperture with German birefringent filters of 0.5 A band pass, and one station is using a spectroheliograph.

Electronic devices designed to detect solar flares by means of their ionospheric effects on cosmic radio noise and atmospheric noise are being installed at High Altitude and Sacramento Peak Observatories. Similar instruments are in operation at McMath-Hulbert Observatory and Renssalaer Polytechnic Institute.

The Sacramento Peak and High Altitude Observatories have extensive programs for observation of several different aspects of the variations of the sun's corona, so important for the formation of solar radio noise, and for the emission of soft X-rays which are absorbed in the ionosphere of the earth.

Solar radio noise, in the meter wavelength region of the spectrum, is being observed at the following locations: NRL; Sacramento Peak Observatory through the Harvard College Observatory Project at Fort Davis, Texas; University of Michigan; National Bureau of Standards (NBS); Cornell University; and the University of Hawaii. Two of these stations will operate radio frequency spectrographs with a wide frequency range.

McMath-Hulbert and High Altitude Observatories are recording the life history of the variations of the width and intensity of spectrum lines of certain major flares.

One of the most interesting and potentially valuable features of the US-IGY program is

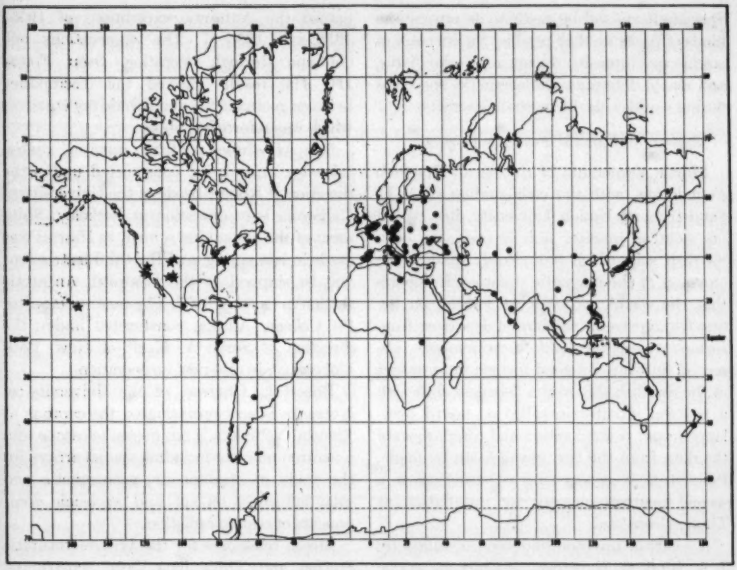

Fig. 1. *IGY Solar Activity Stations. Stars represent U. S. stations; dots represent stations of other countries.*

the effort at Mount Wilson and Palomar Mountain Observatories to map the magnetic field pattern of the entire solar disk on a day-to-day basis. An instrument which can observe the magnetic field strength distribution, at weak field strengths over the solar disk, has been built by Horace W. and Harold D. Babcock, using the Zeeman effect on spectrum lines from the sun's surface. It seems highly likely that the surface layer magnetic fields so observed also relate to the magnetic field patterns in the lower atmospheric layers of the sun. These are likely, in turn, to control the emission of electric particles. Thus, it appears very probable that the intercomparisons of the magnetic field data with the patterns of occurrence of auroras, geomagnetic field variations, and ionospheric effects, will yield large returns. The magnetic studies are also very important to the understanding of the emission of cosmic rays from solar flares.

Cosmic Ray Program

In the US-IGY program, nine projects are using standard neutron monitor or meson telescopes for continuous registration of cosmic ray intensity. Eleven projects will make use of balloon flights. Most of these involve experiments to determine the mass and charge spectra of the primary cosmic rays and whether these change with time.

Special efforts will be made to determine the kinds of particles that produce the increase of cosmic ray intensity during zone solar flares, and also to determine changes in the spectrum during world-wide decreases in intensity.

Neutron and Meson Telescope Projects

Martin Pomerantz of the Bartol Research Foundation, with the collaboration of A. E. Sandström of Upsala University, has placed one neutron monitor unit in operation on a Swedish ship which has already made some crossings of the magnetic equator. He reports that the cosmic ray equator located on the first trip represents the largest departure from surface magnetic field measurements observed thus far. By good fortune the voyages of the Swedish ship and a Japanese ship with a neutron monitor installed on board overlapped, and normalization and comparison of the data from the two voyages can be made. Pomerantz is supervising construction of a second neutron monitor for installation at Thule, Greenland.

A neutron monitor had been installed by J. A. Simpson, University of Chicago, on one of the US Navy icebreakers which accompanied the Antarctic expeditions of 1955–1956 and 1956–57. The observations will continue through operation Deep Freeze III. The results showed the discrepancy between geomagnetic and cosmic ray equators which was referred to above.

One of three neutron monitor meson telescope units being constructed under the direction of Robert Brode of the University of California is in operation at Berkeley. Shipment of the second instrument to Hawaii was made in late spring, and the third instrument will be shipped to the Ellsworth Antarctic station in October 1957. The neutron monitor for College, Alaska, constructed under the direction of Serge A. Korff of New York University, is also now in operation.

Robert L. Chasson, of the University of Nebraska is now operating on the campus at Lincoln, Nebraska, a mu meson telescope and a neutron monitor including special arrays for the study of atmospheric, geomagnetic and solar influences on mu and nucleonic components of cosmic radiation.

Meson telescopes for the Wilkes Antarctic Station and Thule have been constructed under the direction of S. F. Singer, Univer-

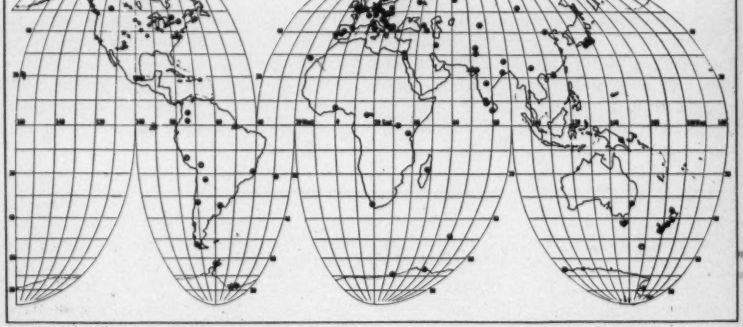

Fig. 2. *IGY Cosmic Ray Stations. Black stars represent U. S. stations; black dots represent stations of other countries; white stars in black circles represent cooperative stations; and black arrows represent balloon launching sites*

sity of Maryland. The telescopes have been shipped to their sites and the Antarctic equipment is now nearly installed.

Balloon Projects

The heavy component of primary cosmic radiation will be investigated by examining photographic emulsions exposed in high altitude balloon flights. The charge of the heavy primaries will be measured by a number of techniques which were used in a series of pre-IGY measurements reported by the project director, W. F. G. Swann of the Bartol Research Foundation. Results of these experiments will be integrated with those from the programs of M. A. Pomerantz of the same institution. He will investigate the correlation of solar activity with high altitude primary cosmic ray intensity through use of balloons carrying various types of charged-particle detectors.

Investigation of the isotopic constitution of cosmic radiation at balloon altitudes will be carried out by Marcel Schein of the University of Chicago. The heavy nuclei component of the primary cosmic radiation will be studied in great detail by exposure of blocks of large size to cosmic radiation at different latitudes. Already, heavy nuclei have been investigated by means of two balloon ascents —in Texas in January 1956 and in Guam in February 1957—by courtesy of ONR as part of its Skyhook balloon program. Techniques were developed for the identification of heavy nuclei, and a preliminary Z spectrum has been obtained from the Texas emulsion stacks. Furthermore, interesting results have been obtained on the breakup processes of heavy nuclei. These results are in reasonably good agreement with fragmentation probabilities of medium heavy elements (C,N,O) obtained in other laboratories. However, as far as the heavy nuclei of Z greater than 12 are concerned, a considerably higher value has been obtained for the fragmentation probabilities than those reported by some leading laboratories.

Under Herman Yagoda, the flux of low energy heavy primary cosmic rays will be studied by exposure of a series of small emulsion blocks carried to high altitude on balloon flights in polar areas. Preliminary control data for such exposures were provided when a stack of emulsions was flown to a peak altitude of 120,000 feet by the US Air Force at geomagnetic latitude 55°N.

Emulsion studies of heavy primary cosmic rays will be made under the direction of J. J. Lord, University of Washington, as a part of the ONR program for balloon flights during the IGY. Heavy cosmic rays of primary nuclei with Z equal to or greater than 10 will be investigated by study of emulsions under the direction of Otis B. Young of Southern Illinois University. Emulsions will be exposed by means of flights in the extreme north and south and at intermediate latitudes.

In a program directed by H. V. Neher, California Institute of Technology, ionization chambers will be flown in a number of simultaneous balloon flights. These will provide information on the latitude effect, fluctuations in the primary radiation at different latitudes, possible asymmetry conditions existing between the poles or poles and equator, and high altitude cosmic ray phenomena at this phase of the solar cycle as compared with other phases. Expeditions are planned to Thule in the summer of 1957, to Thule by ship in the summer of 1958, and to the Antarctic by ship in the fall of 1958. Simultaneous releases will be made from the Thule-bound ship and from Bismarck, N. D., and also from the ship bound for the Antarctic and from New Zealand. All parts of the ionization chambers have been completed, and twenty of them, a sufficient number for the 1957 summer operations, have been assembled. Design of the amplifier unit is proceeding, and a new receiver is being developed which is considerably lighter than the one used previously.

A project for the measurement of composition and intensity of primary cosmic radiations will be carried out under John A. Simpson, Institute of Nuclear Studies, University of Chicago. Proton and heavy particle intensities at the top of the atmos-

phere will be measured as the total intensity changes with time. A special effort will be made to study kinds of particles arriving at times of cosmic ray intensity increases.

Balloon flights will be made at Prince Albert, British Columbia, through the cooperation of D. C. Rose, Chairman, Coordinating Committee, Canadian IGY Program. The US Air Force Office of Scientific Research (AFOSR) is providing support as part of its cosmic ray program.

Counter studies of the spectrum of primary radiation and its time variations will be directed by Serge A. Korff of New York University. By means of high altitude balloon flights the charge and mass spectrum of the primary cosmic radiation will be investigated, particularly at times of solar disturbances. Korff reported earlier that construction of equipment for the summer flights was continuing, that flights would probably be made from an airport near Minneapolis and that flights were being arranged to be as nearly simultaneous as possible with other balloon flights in Texas. A search will be made there for primary neutrons from the sun. Flights will be made just around the 'knee' of the latitude effect during normal times and during periods of solar disturbances. These should yield information on the energy distribution of the incoming particles and especially of neutrons. Plans are under way for flights from Lufkin, Texas.

An experiment to measure as continuously as possible the cosmic ray intensity at the top of the atmosphere at Minneapolis will be directed by E. P. Ney and J. R. Winckler of the University of Minnesota. A special balloon was developed at the University of Minnesota for this experiment. It is capable of carrying a 30-lb payload to 100,000 ft and remaining there for a period of about 24 hours. Equipment on the flights will include a counting device under development and light-weight oriented plates of photographic emulsion. Several types of monitors were considered and built, and several preliminary flights were made using some of the developmental apparatus flown on large, constant-level skyhook balloons.

The preliminary flights with ionization chambers showed a strong latitude effect at constant level so that latitude changes as small as 7 miles can be detected. Winckler has remarked that this suggests an auxiliary use for the IGY flights, namely, to map out cosmic ray grids for the north-central states built up out of E-W, N-S trajectories. Cosmic ray latitude lines could be drawn and the equivalent magnetic pole for cosmic radiation located. The preliminary experiments also showed that fluctuations in the pulse interval in the ionization chamber can be attributed to the heavy nuclei in the primaries, with the possibility of studying fluctuations of heavy nuclei separate from fluctuations of the singly-charged component. The mean ionization per particle and its change with latitude, atmospheric depth, or time can also be observed.

Studies of solar effects on cosmic rays at high altitude in the Arctic will be carried out under the direction of Kinsey A. Anderson of the State University of Iowa. Observations are planned to include the rates of a single Geiger counter, of a vertical counter telescope and of a single scintillation crystal. The differing effects of arriving solar particles on the various counting devices will yield new information about their nature. During January, transistorized scalers of the type to be used in IGY flights were flown in skyhook balloons during an expedition to Guam sponsored by the ONR. The scalers performed well; as a result, 20 such circuits are under construction for the IGY experiments. Assembly of the ionization chambers has begun, and in March an order was placed for 21 polyethylene balloons.

M. F. Kaplon of the University of Rochester will expose a large stack of stripped emulsion on a balloon flight at a latitude near or above the cosmic ray knee and at a residual atmosphere of 8 gm/cm^2 or less for 8 to 16 hours. From the exposed plates,

the proton energy spectrum will be investigated and a search made for deuterium or tritium. The low energy end of the spectrum will also be studied and the interactions of nuclei examined. A study of high-energy cosmic ray interactions will be made as well. A special stack flipper to orient the emulsion properly is under construction. Emulsions will also be flown, probably in Minnesota, as part of a larger stack in collaboration with M. Friedlander of Washington University at St. Louis.

Special Projects

High-speed cosmic ray intensity fluctuations will be investigated at various latitudes during periods of solar activity, particularly solar flares, by S. F. Singer of the University of Maryland. Two trays of cosmic ray counters of large area will be kept in contact. Their outputs will be fed to a coincidence circuit driving a count rate meter. The observations will be made at high altitude at Sacramento Peak, New Mexico, in the Canadian Rockies, and in aircraft.

Measurements of zenith angle dependence will be made under the direction of Nelson M. Duller of the University of Missouri. A telescope and integral energy meson detector will be used to discriminate against mu mesons of energies less than a fixed cut-off energy and to accept all mesons above this energy at various angles. Detection is being attempted by a direct method using a large electromagnet as a momentum spectrometer, and by an indirect method based on the fact that as the energy of a mu meson increases, its probability of producing a large cascade shower (electronic) in a thick lead shield increases. From preliminary data with a simple multiple-coincidence shower detector, Duller has indicated that analysis of the early recorded data seemed tentatively to confirm that the intensity of shower-producing particles appears to increase at zenith angles away from the vertical.

Paul H. Barrett of the University of California will direct a project for the detection of air showers produced by cosmic ray particles with energies in the range 10^{17} –10^{19} electron volts by means of a large area Cerenkov counter consisting of six stations on the Santa Barbara College campus. Four stations are in operation and data are being recorded at the central station on an Esterline-Angus recorder. Final adjustment of receivers and routine checking procedures are still to be worked out.

Studies of the semi-diurnal planetary variation of atmospheric pressure will be made by operating two pieces of counter-tube recording equipment at high altitude at the laboratory at Chacaltaya, Bolivia, under the direction of Victor H. Regener of the University of New Mexico. Present plans are for operations to begin before 1958.

Finally, Leticia del Rosario of the University of Puerto Rico will measure the sudden increase and slow decrease in cosmic ray intensity at the time of solar flares and attempt to correlate the results with similar measurements taken with neutron counters. Installation of equipment for these special projects should now be complete.

Geomagnetism Program

The magnetic field of the earth, which has been used in surveying and navigation for several centuries, has been under continuous routine observation for more than one hundred years by magnetic observatories distributed over the earth. At the present time there are more than 80 such observatories maintained by various countries.

While the magnetic field is for the most part stable and unchanging over long

periods, the field does undergo some variations. These may be slow, measured in years, or rapid, measured in days, hours, minutes, and seconds. The variations, although they involve large amounts of energy (they envelop the entire earth), rarely amount to more than about two percent of the earth's field and are seldom large enough to disturb a mariner's compass. Mathematical analysis has shown that the permanent field and the very slow variations are due to magnetic effects in the interior of the earth's crust and that the more rapid fluctuations arise from influences external to the earth—in the upper atmosphere or even higher.

During the IGY, many of the US geomagnetic observatories will make absolute measurements of the earth's field. This information is valuable for studying secular or long time variations and for preparing magnetic maps for navigational purposes. The major part of the US program, however, is devoted to experiments designed to yield information about the disturbances, or magnetic storms. The disturbances are known to appear sometimes only in polar latitudes with no effect at the equator, and sometimes simultaneously over the entire earth; fluctuations at the equator with no effects at the poles are never observed.

The fact that the magnetic disturbances increase and decrease with sunspot number is considered adequate proof, and indeed at present the only proof, that they are the result of bursts of radiation of some sort from the sun. The type of radiation is not known, but charged particles, ultraviolet light, and X-rays have been suggested. The manner in which the bursts might cause the magnetic disturbances has been treated in several theories, but none is considered completely successful.

World-wide analysis shows that the main features of the magnetic disturbances are such as would be caused by three great electric currents, measured in hundreds of thousands of amperes, in the upper atmosphere. These three currents are in the zones of maximum auroral frequency in the north and south polar regions and around the earth above the magnetic equator. The latter current appears to have an extraordinary belt of greatly increased intensity concentrated in a narrow width of only about 200 km. The demonstration of the

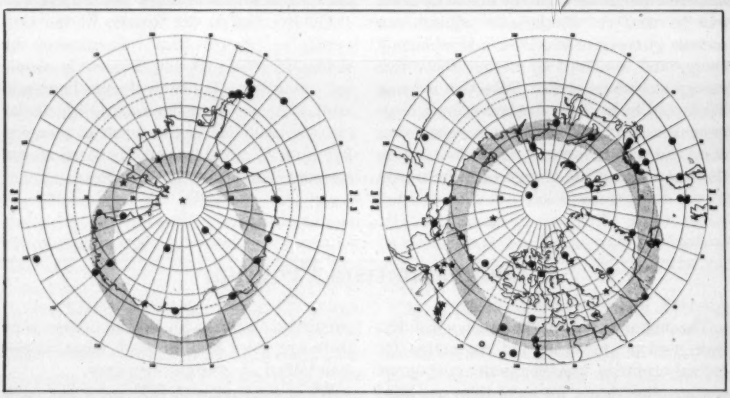

Fig. 3. *IGY Geomagnetic Stations. Black stars represent U. S. stations; black dots represent stations of other countries; and white stars in black circles represent cooperative stations. Stippled bands are zones of maximum auroral frequency.*

existence of these currents, their nature, and their cause is an outstanding problem of geomagnetism.

With a single observatory, only a limited amount of information may be learned about an overhead electric current, whereas much more information may be learned from a network of observatories. For this reason, several networks or chains of stations were established for the US-IGY program.

The US Department of Commerce Coast and Geodetic Survey (C&GS) has in the past operated most magnetic observatories in the United States, under the Division of Geophysics. With a few exceptions, the IGY observatories will also be operated by the C&GS.

In Alaska, in addition to the standard observatories at Pt. Barrow, Sitka, and College, a five-station network is in operation at Anchorage, Barter Island, Ft. Yukon, Kotzebue, and Northway. An instrument is also in operation at Drifting Station A, about 600 miles north of Pt. Barrow.

At College, Alaska, a special instrument designed by J. H. Nelson, of the C&GS, the differential magnetograph, is in operation measuring the space gradients of the magnetic fluctuations. Similar measurements but with standard equipment are now also being made at Healy and Big Delta.

In the United States, an east-west network of five stations, with the main location at Climax, Colorado, and a short north-south arm with two additional stations, are designed to study the overhead currents in detail, and to provide information on any possible connection between meteorological and geomagnetic effects, possibly involving ionized air circulating in wind systems in the lower ionosphere.

In cooperation with Albert Giesecke, Jr., Director of the Huancayo Geophysical Institute in Peru, Scott Forbush of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington is supervising the establishment of a five-station fine-spaced network, centered at Huancayo very near the geomagnetic equator, to study the equatorial current mentioned above.

In the Pacific, the geomagnetic equator passes near the Line Islands in the Eastern Pacific, and the Palau Islands in the Western Pacific. The Scripps Institution of Oceanography, in cooperation with the C&GS, has established geophysical observatories in the Line Islands and has magnetic instruments installed at Jarvis (on the magnetic equator), Palmyra and Fanning Islands. The C&GS is operating the stations at Koror (on the magnetic equator) and Guam.

In a special study of higher frequency variations of the magnetic field, Elwood Maple of the Geophysics Research Directorate (GRD) of the Air Force Cambridge Research Center and A. Raymond Jordan of the Denver Research Institute of the University of Denver, are establishing five stations to record magnetic variations in the frequency range 1–50 cps. These stations at College (now operating), Thule, Cambridge, Denver, and a fifth either in Puerto Rico or Florida, will gather information bearing on the question whether the fluctuations in this band are due to electromagnetic radiation from distant lightning discharges or from induction fields such as those set up by the ionospheric currents overhead.

Rapid-run magnetic instruments have been installed in a number of observatories to study the fine detail of the magnetic fluctuations. The speed of the recorder allows resolution of disturbances of six- to eight-second periods.

In the Antarctic, the magnetic observatories will provide new information on the absolute value of the field and will help map the zone of maximum auroral frequency, known at present only from inadequately spaced observations. Standard magnetic observatories have been put into operation at Little America, Byrd, and Wilkes Stations. Variation instruments only

are in operation at the Pole Station and Cape Adare (in cooperation with New Zealand).

Besides the measurements at land observatories, rockets, and possibly the earth satellite itself, will carry magnetometers up into the regions where the currents are suspected to exist. These experiments may give the ultimate answer as to the existence of the currents and their location.

Ionospheric Physics Program

The heart of the program of ionospheric observations is the use of sweep-frequency sounders to transmit pulses vertically and record the reflected echoes from the ionosphere in the form of ionograms. The United States soundings network has been expanded for the IGY by the Central Radio Propagation Laboratory (CRPL) of NBS and by the US Army Signal Corps Radio Propagation Agency (SCRPA). There are six stations in the Antarctic (one operated jointly with New Zealand), one on the Arctic ice island T-3, and others at Thule, St. Johns (Newfoundland), and Grand Bahama Island along the northern part of the 75°W meridian. Six South American stations have been supplied equipment for the southern extent of 75°W where a closely-spaced network is provided for the study of ionospheric fine structure near the geomagnetic equator. All but five of the planned vertical sounding stations were in operation at the beginning of the IGY, but these will soon be operating since all equipment had been delivered to the sites at that time.

True ionospheric reflection heights can be obtained easily from ionograms only by processing the scaled data with digital computors. For four of the stations (Washington, Panama, and Talara and Huancayo in Peru), this will be performed in the United States at the Pennsylvania State University under the supervision of A. H. Waynick. Test computations have already been carried out.

Ionospheric absorption can be studied by comparing the amplitudes of reflected pulses with those of incident pulses, a technique used at the Pennsylvania State University where the necessary equipment is now in operation. Absorption is also being studied during the IGY by observation of galactic radio noise received through the ionosphere at higher frequencies. This method was developed by C. G. Little of the University of Alaska, and a network of eight auroral zone stations in Alaska, two in Quebec and Sweden, together with a middle latitude network of five stations in the United States, is under his coordination. About two months' delay is expected in installing the stations.

The scintillations of radio stars, as observed from three receivers spaced a mile or two apart on the ground, provide a means of studying ionospheric movements. At the University of Virginia, a station under E. C. Stevenson has begun operations. At the University of Puerto Rico, other ionospheric drift observations have been made for several years by reception of pulsed echoes at three closely-spaced receivers. This program is continuing during the IGY under the direction of Miguel Wiewall. The analysis of ionospheric drift data is difficult, and G. F. Gassmann of GRD will provide additional information by making observations with an airborne ionospheric recorder. The aircraft was to leave for Europe on July 20 and will return at a later date to make flights in the western hemisphere for the study of oblique reflections and atmospheric tides in equatorial regions.

If transmissions are made over radio

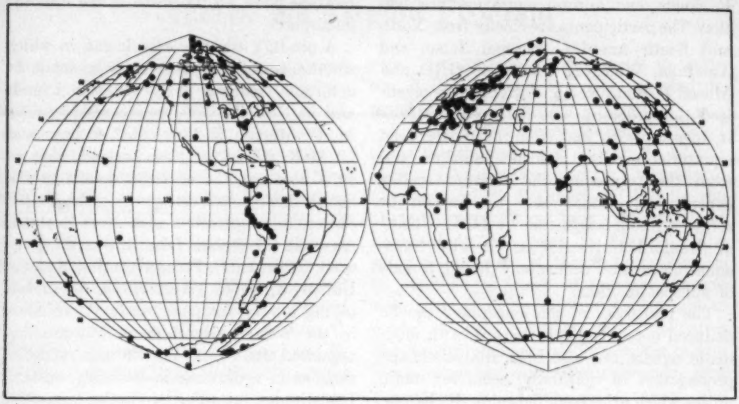

Fig. 4. *IGY Ionospheric Physics—Vertical Incidence Stations.*

propagation paths obliquely incident upon the ionosphere, such as those used for long distance communication, backscatter occurs at the ground beyond the point of ionospheric reflection; it can be observed at the transmitting site with appropriate techniques. From such observations, equivalent vertical incidence properties of the ionosphere can be deduced and meteoric and auroral ionization columns and sporadic ionization can be studied.

In a unique United States program, A. M. Peterson of Stanford University is supervising a network of backscatter stations which cover North America and include two stations in Brazil and Australia. Rotating single-frequency directional antennas will be used to receive the echoes, recording in polar plot (ppi) form at three frequencies. The stations were expected to become operational during July and August. M. G. Morgan of Dartmouth College will supervise sweep frequency backscatter transmissions southward out of the auroral zone from Knob Lake, Canada, beginning in the fall.

'Sporadic E ionization at the 100 km level continues to be an enigma. E. K. Smith of CRPL has set up an experiment to verify reports, from Japanese workers, of unusually high reflection coefficients from sporadic E. Transmissions will be sent from Okinawa to the Philippines and Japan, from Panama to Cuba, and from Illinois to Colorado. Stations will not be installed, however, before September 1957.

Forward scattering from the lower ionosphere has been widely studied in the United States and the Arctic. However, no equatorial zone measurements have been made in South America, so CRPL is conducting a pulse experiment there with transmission along and across the geomagnetic equator. The program is under the direction of K. L. Bowles and Robert S. Cohen. The circuits will be operational in the fall.

During the last sunspot maximum, amateur radio hams discovered the phenomenon of transequatorial scatter which is manifested over distances too great to be accounted for by forward scattering from the lower ionosphere. Accordingly, the American Radio Relay League (ARRL) is participating in the IGY through the observation and reporting of two-way contacts by means of transequatorial scatter, sporadic

E clouds, and auroral ionization propagation. The participants are chiefly from North and South America, Europe, Japan and Australia. Wolfgang Pfister of GRD and Mason P. Southworth, ARRL, have organized this program. The data realized from it, together with that from the close-spaced equatorial vertical incidence stations and from the transequatorial forward scatter experiments, should help to confirm or refute a recent suggestion by O. G. Villard of Stanford University as to why transequatorial scatter occurs only during periods of sunspot maxima.

The properties of the ionosphere can be deduced not only by probing it with man-made signals, but also from analysis of the propagation of naturally occurring radio pulses which arise from lightning discharges. In a program expanded for the IGY by CRPL and under the direction of W. Q. Crichlow, fifteen recording stations have been established at locations widely distributed over the earth. They will record radio noise continuously on eight frequencies.

Lightning discharges produce most of their radiated energy at low frequencies which overlap the audio-frequency range. The sferics so produced become 'whistlers' —tones of descending pitch—upon being propagated dispersively over long ionospheric paths because the propagation speed is then a function of frequency. According to a theory of L. R. O. Storey, whistler propagation begins at the point of lightning discharges, follows upwards along the lines of the earth's magnetic field into the far outer atmosphere and returns to the symmetrical point on the earth in the opposite hemisphere.

A pre-IGY whistler experiment, in which simultaneous measurements were made at conjugate locations in the Aleutian Islands and in New Zealand, was carried out by M. G. Morgan of Dartmouth College and G. McK. Allcock of New Zealand. The results bore out the essential details of the Storey theory. As a consequence, the United States, in cooperation with New Zealand, Australia (Macquarie Island), Canada, Denmark (Greenland), Peru, Argentina, and the United Kingdom (Antarctica), is undertaking a very complete study of whistlers in the Western Hemisphere. Morgan has organized the work for thirteen whistler stations in a network in generally eastern US latitudes, including two in the Antarctic. R. A. Helliwell of Stanford University has organized the program for nine stations in a chain of locations in western US latitudes. Sferics locations at some stations will be obtained by radio direction finding. In the North Atlantic, these sferics data will be supplied by the Air Weather Service of the US Air Force, and in the North Pacific by additional equipment at certain of the whistler stations. The investigation of sferics phenomena will also include certain other isolated vlf emissions such as 'hiss' and the 'dawn chorus' which are heard on whistler observing apparatus.

A large proportion of the experimental ionospheric program is operational or nearly so. A considerable amount of data had been taken before the formal opening of the IGY, and it is expected that most stations not yet established will achieve operational status within a short time.

Aurora and Airglow Program

The principle synoptic auroral observational program employs all-sky cameras which photograph the whole sky. The 29 cameras planned for networks in the Arctic, the Antarctic, and the United States have all been constructed and shipped to the field stations. All are not yet in operation, however, for those in northern latitudes will first be employed in September when it becomes dark enough to make observations. These auroral observations are supervised by C. T. Elvey, Director of the Geophysical Institute at the University of Alaska, C. W. Gartlein of Cornell University, and N. J. Oliver of GRD, Air Force Cambridge Research Center.

The final model of the ascaugraph, an instrument for the semi-automatic reduction of all-sky camera films, is under construction. Photographic processing equipment has been installed at College, Alaska, where most of the all-sky camera film will be developed.

Visual observations of auroras by 120 US Weather Bureau Stations and 56 volunteer stations have been in progress for some time. The stations report directly to Gartlein at Ithaca where the data is stored on punched cards for further analysis.

Eighteen patrol spectrographs constructed under the supervision of Joseph W. Chamberlain of Yerkes Observatory, University of Chicago, and N. J. Oliver of GRD for the auroral program have been completed and delivered to the sites as planned. The primary objective of these observations is to establish a profile of spectral changes with latitude in the auroral display and to study auroral variations with time after the display commences. Two of the instruments, together with all-sky cameras, were functioning at Yerkes Observatory and Shingleton, Michigan, during the very intense auroral display of March 2, 1957. Four scanning spectrometers, which are to provide information on rapid changes in the auroral spectrum during auroral displays, have also been constructed. Two of the instruments have been shipped, one to Yerkes Observatory, and the other to the Geophysical Institute of the University of

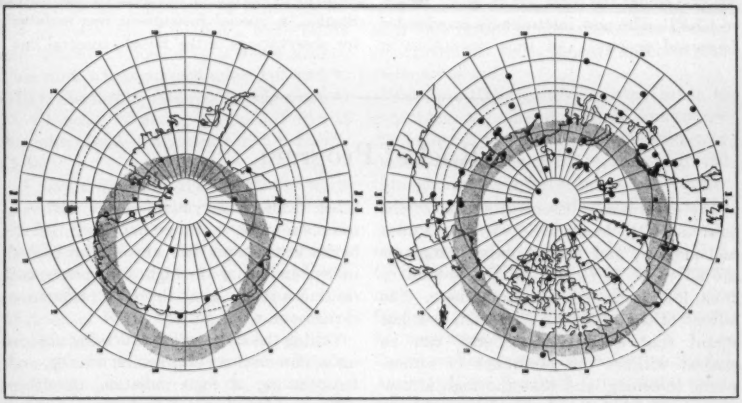

Fig. 5. *IGY Aurora All-Sky Camera Stations. Black stars represent U. S. stations; black dots represent stations of other countries; and white stars in black circles represent cooperative stations. Stippled bands are zones of maximum auroral frequency.*

Alaska. One of the remaining instruments is planned for operation in Little America and the other for operation aboard an aircraft operated by GRD.

A prototype unit has been built for the auroral radar program and has been tested over a period of several months. The remaining nine units for stations in Alaska, the United States, and Macquarie Island are now under construction; installation of most of the units were to be completed prior to September 1957, making it possible to operate through the September equinoctial period, a maximum of auroral activity.

The measurement of ionospheric absorption in auroral regions by observation of cosmic noise is to be performed on an instrument called the riometer designed at the Geophysical Institute, University of Alaska. The program is a joint undertaking of ionosphere and aurora groups. Modifications of this prototype unit design have necessitated a delay in installation but, as indicated in the report on the ionosphere program, installation of all 13 monitors should be completed before September 1957.

Improved instrumentation for photometric observation of the airglow has been developed under the direction of F. E. Roach of CRPL. The new instruments provide for improved spectral and time resolution in observing H-beta, OH, oxygen green and red, and sodium emissions. These instruments have been shipped to the observing sites and those in the lower latitudes are in operation. Those in the higher latitudes will begin operation when the nights become dark enough.

The airglow photoelectric photometers record airglow intensities in the particular spectral regions of interest for a series of specified directions spaced over the sky in elevation and azimuth. The intensity curves obtained are read, and the values are transferred to punch cards which are processed in a computer at Boulder, Colorado, to make necessary corrections to the raw data. The computer prints the data in the form of a sky chart of absolute intensities of emission in a particular spectral region as observed at a given time in the various directions. Data is already being processed in this way.

In the Antarctic, two special programs have been undertaken by IGY observers. At the Pole Station, the patrol spectrograph was mounted on a turntable revolving at one revolution per day for study of the twilight spectrum of the sun. At Ellsworth Station, a special instrument was installed for observations of the H-beta spectral line.

Rocket Program

The experiments described above for the solar activity, ionospheric physics, aurora and airglow, and geomagnetism programs are all to be performed on the ground or from low levels in the atmosphere. The advent of the rocket as a research tool has meant that solar characteristics can be studied without the hindrance of atmospheric screening, and that the high atmosphere itself can be studied with instruments situated within the medium. Thus, the rocket experiments supplement those in the other fields. Observation of the high atmosphere with both ground and rocket-borne instruments has already broadened understanding of the high atmosphere and continues to do so as the IGY program is carried out.

During the IGY, rockets are being used to make observations of pressure, density, and temperature, of color radiation, the ionosphere, atmospheric composition, auroral particles and ultraviolet radiation, and of magnetic fields. These flights will be

launched at latitudes all the way from the Arctic to the Antarctic, but especially at Ft. Churchill, Canada, located in the middle of the auroral zone.

A pre-IGY rocketry program has been carried out over the past year with 24 test flights, including 19 small rockets and 5 Aerobees, in order to perfect techniques and instrumentation.

In the summer and fall of 1956, six Nike-Cajun rockets were instrumented for measurement of atmospheric density by the falling sphere method under the direction of L. M. Jones of the University of Michigan. In this experiment a metal sphere is ejected from the rocket. Telemetered information indicates the deceleration due to atmospheric drag on the sphere, permitting a determination of density. The experiments were sponsored by GRD, of the Air Force Cambridge Research Center, and the National Advisory Committee for Aeronautics. All six flights were successful, the last five having been made from the USS *Rushmore* at sea and attaining more than 100 miles in peak altitude. Data have not yet been reduced.

Two rockets were prepared under N. W. Spencer of the University of Michigan for the measurement of pressure, temperature and density by means of pressure gauges. This work was performed under contract to GRD. The flights were successfully made at Ft. Churchill, attaining altitudes of 70 and 90 miles. Data analyses are not yet completed.

A similar pressure experiment was made in an Aerobee-Hi fired in November 1956 at Ft. Churchill under the supervision of H. E. LaGow of NRL. This flight also carried photon counters prepared by Herbert Friedman and Richard Tousey, of the Optics Division of NRL, for the measurement of soft X-rays and the Lyman alpha line from the sun. From analysis of such altitude-intensity data, atmospheric constituent densities can be determined, but in this experiment the rocket rolled so slowly that the photon counters were presented to the sun too infrequently to obtain reliable results.

Another November flight at Ft. Churchill was instrumented by the University of Michigan for the Signal Corps Engineering Laboratories to obtain temperature and wind data by the exploding-grenade technique. The primary data consist of sound transit times to the ground.

The technique of launching rockets on short notice from balloons already floating at high levels was developed for the study of solar flares. Ten such 'rockoons' were launched in July 1956 by a group under Herbert Friedman, NRL, off the coast of San Diego, California. One flare was detected during these firings. Measurements revealed an X-ray flash extending the spectrum down to nearly 3A and persisting well after the Lyman alpha emission had decayed to normal. At its short wavelength limit it resembled the emission of a four-million-degree thermal source. Although the flare was small the X-ray intensity was theoretically sufficient to produce a substantial increase in D-region electron density between 75 and 85 km. On the basis of the experience gained from this pre-IGY flare experiment it was decided to alter the IGY solar flare firings to utilize the Nike-Deacon combination at Point Mugu, California (San Nicholas Island).

Two pre-IGY launchings were made to determine the distribution of ionospheric charge density by means of radio frequency transmissions between the rocket and ground through the ionosphere. In one experiment, an Aerobee-Hi was launched at Ft. Churchill under the direction of J. E. Jackson of NRL; the experimental technique developed by J. C. Seddon of NRL was used. This experiment was successful although rocket performance was poor. In another experiment to determine electron densities, a Nike-Cajun rocket was instrumented by the US Army Ballistic Research Laboratories under the direction of W. W. Berning and flown at White Sands, New Mexico. This flight was instrumented with the DOVAP system,

and was primarily a test of the suitability of the rocket for such measurements.

Determination of the atmospheric composition at high altitudes is feasible by flying radio-frequency mass spectrometers in rockets. An Aerobee-Hi, instrumented by Edith Meadows and C. Y. Johnson of NRL with three Bennett radio frequency spectrometers, was flown from Ft. Churchill in November 1956. Changes in the ratio of argon to molecular nitrogen, measured by the neutral gas spectrometer, indicated that diffusive separation of the atmospheric gases started between 100 and 110 km. As the rocket rose, peaks of mass numbers 16 and 30 became increasingly important components of the spectra. At 224 km, the highest altitude at which a neutral gas spectrum was obtained, amplitudes of masses 16 (O), 28 (N_2), 30 (NO), and 32 (O_2) differed from each other by less than a factor of 3. The amplitude of 32 was undoubtedly enhanced by the recombination of O atoms on the walls of the inlet tube. Spectra were obtained from a positive ion spectrometer in the mass range 53 to 6 atomic mass units for 375 seconds when the rocket was above 90 km. Mass 30 was the first positive ion detected and remained in the spectra throughout the flight. Positive ions of mass 32 and 16 subsequently appeared. The mass 16 positive ion became the predominant ion with increasing altitude. Two minor positive ions of mass 28 and 18 were detected during the flight. A possible identification of these ions is $32 - O_2^+$, $30 - NO^+$, $28 - N_2^+$, $18 - H_2O^+$, $16 - O^+$. Above 170 km there was indirect evidence of a positive ion with relatively large abundance at mass 63 ± 2 atomic mass units. A spectral peak in the region of mass 46 was detected by the negative ion spectrometer. Nitric acid, one of the rocket's propellants, might have contributed to some of the ion peaks, although data from the neutral gas spectrometer at the nose of the rocket indicated that the rocket was 'clean.'

Observation of auroral particles and ultraviolet radiation by rocket techniques is an important part of the IGY rocket program. Early information was gained by J. A. Van Allen and his colleagues of the State University of Iowa. Their measurements revealed a 'soft radiation' at altitudes of 40–70 km which exhibited the characteristics of X-rays in the 10–100 kev range. Dr. Van Allen concluded that the X-rays are associated with primary auroral radiations but are not themselves primary in nature. During the IGY, attempts will be made to identify the auroral radiation by means of geiger counters, proportional counters, scintillation counters and energy analyzers. In a pre-IGY firing at Ft. Churchill, photon counter measurements were made of the Lyman alpha intensity and of the spectral band 1220-1350A. Each NRL Aerobee launched at night during the IGY at Ft. Churchill will make such measurements.

Van Allen has adapted a proton precession magnetometer to observe the discontinuity of the earth's field upon traversing the ionospheric current system in small Loki rockets employed with the rockoon technique.

A major accomplishment of the pre-IGY rocket program was the establishment of the Ft. Churchill facility. Not only was a large launching complex installed but numerous instrumentation sites also were erected in the area. The entire rocket program was made possible by the help and cooperation of the US Department of Defense and, additionally, in the case of Ft. Churchill, by the help and cooperation of the Canadian government.

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A monthly survey by the U. S. National Committee for the International Geophysical Year. Established by and part of the National Academy of Sciences, the Committee is responsible for the U. S. International Geophysical Year program in which several hundred American scientists are participating and many public and private institutions are cooperating.

Current Sunspot Numbers

The choice of the period July 1957 to December 1958 for the International Geophysical Year was determined in part by the expectation that sunspot frequency would reach a cyclical maximum during this time. Since upper atmosphere effects would then be pronounced, coordinated geophysical studies could greatly increase knowledge of solar-terrestrial relationships. Of considerable scientific interest is the fact that recent sunspot numbers have attained an apparently unprecedented level. Pending final refinement of the data, the particular interval during which peak frequency is reached during the current cycle will not be known precisely. However, the present cycle, which began in 1954, had already reached a count of 169.6 in January 1957. Data reaching as far back as 1755 show no peak as high. The highest previous peak occurred in 1778 (*see Fig. 1*).

Even before the invention of the telescope and the use of that instrument for astronomical purposes, man had noted the appearance now and then of dark areas on the surface of the sun. Then, in 1612, Galileo trained his telescope on the sun and for the first time actually observed the spots in detail. He concluded that they were phenomena on the sun itself, rather than shadows of bodies external to the sun. He also observed the motions of the spots across the face of the sun and postulated that the sun rotates from east to west with a period of somewhat less than a month. Galileo made sunspot maps in 1612 that compare favorably with maps made today with modern small telescopes.

In the 19th century, Sir John Herschel said of sunspots, "Many fanciful notions have been broached on this subject, but only one seems to have any degree of physical probability, viz., that they are the dark, solid body of the sun itself, laid bare to our view..." Although astronomers now know that the sun is a gaseous body and has no dark, solid interior, the exact nature of sunspots and their relation to other phenomena on the surface of the sun are today matters of considerable scientific disagreement and discussion.

Since about 1749, sunspots have been observed on a regular basis. It was not until 1834, however, that a Swiss Astronomer, R. Wolf, of the Federal Observatory, Zurich, devised a standardized method which is still in use. Wolf's method takes into account the number of groups as well as of individual spots. The daily sunspot number, Rn, is determined as follows:

$$Rn = k(10g + s)$$

where g is the number of groups visible on the disc, s is the number of individual spots, and k is a constant adjusting the number for the "personal equation" of the observatory, taking into account average visibility, type

of equipment, variability between observers, etc. The sunspot number is determined daily by observatories throughout the world.

The daily numbers fluctuate widely and a first smoothing is obtained by averaging over a month. These monthly values are further smoothed by computing running means for a year, which gives the mean in the middle of the yearly period. Finally, two consecutive means are averaged, giving the Zurich number for a month. These final monthly numbers are shown in Fig. 1, extending back to 1755. It is seen from the figure that there is an average periodicity of somewhat more than 11 years, measured from minimum to minimum, but the individual cycles vary from about 9 to 13 years. The present collection and publication of sunspot numbers is being undertaken by the Swiss Federal Observatory, Zurich, under the direction of M. Waldmeier.

As can also be seen from the figure, the individual cycles vary considerably in the peak counts reached at the maximum; there is a factor of about three between the most active cycles and the least active ones. The last complete cycle was one of high activity. The maximum smoothed count, 151.8, occurred late in 1947. The present cycle, which began in 1954, had already reached a count of 169.6 in January (represented by a broken line on the graph). Unsmoothed counts from recent months have been large, especially for the period just before the IGY began officially, and it is conceivable that when the smoothed values are obtained they will show that the maximum actually occurred during this pre-IGY period.

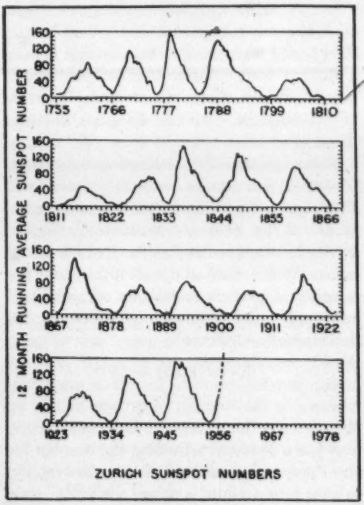

FIG. 1.

It should be pointed out, however, that the IGY was designated as far back as the closing years of the previous sunspot cycle and that considerable solar activity takes place during the entire period of maximum. For individual months the unsmoothed values range widely: there were no sunspots at all observed in January 1954, while in June 1957 the sun was very active and the count reached 205.6.

As in Herschel's time, sunspots are still little understood. They appear dark but only in contrast to the surrounding photosphere; the temperature of the spots can be as low as 4500°K, or 1500°K less than that of the surface. Small spots sometimes occur alone, but rarely last for more than a few days; some large groups cover a few billion square miles and may last for a considerable number of solar revolutions.

The sunspots themselves vary greatly in size, from those large enough to be visible without a telescope, giants as much as 50,000 miles in diameter, to the very small ones, specks only 500 miles across.

Sunspots are not known to occur at solar latitudes higher than about 45°. During periods of least solar activity, small spots form at the larger "allowed" latitudes; as the activity builds up, the spots grow in size, forming at lower and lower latitudes until, during maximum, most of the spots are within plus or minus 10° of the solar equator.

The magnetic fields of sunspots are undergoing concentrated study. Fields have been observed as great as 4000 gauss, or 8000

times that of the maximum intensity of the earth's field at its surface. It has also been noted that sunspots often occur in pairs in an east-west symmetry and it has been found that for a particular cycle the fields will have a uniform distribution of polarity; that is, if the easternmost spot has a north polarity, its western dual has a south polarity. In the opposite hemisphere, the relationship is reversed, and in the subsequent cycle the entire pattern will be reversed.

Many solar phenomena are associated with sunspots, although the mechanisms involved are a matter of conjecture only. Flares are ejections of very hot and active material from the sun's surface accompanied by intense radiation of hydrogen light from the Balmer and Lyman line series far out into the ultraviolet and X-ray region below 100A wavelength. They always erupt from sunspot regions or regions of very recent spot activity. On the other hand, the prominences, which originate at higher levels, do not always occur in association with spots. When ejective prominences occur on the solar limb, they are a most impressive phenomenon, shooting material some hundreds of thousands of miles out into the corona at speeds sometimes greater than 500 miles/sec. Recent motion pictures of prominences and arches at the limb indicate the influence of magnetic fields on the motion of the prominence gases. At times it seems as if the supporting forces are insufficient, so that the prominences and arches materialize above the solar surface and then fall back into the surface.

When the surface of the sun is photographed through a narrow band filter in the light of highly ionized calcium, the solar disc is mottled in appearance; large disturbed areas, called plages, are apparent. Plages probably are disturbances in the chromosphere, at higher levels than the sunspots, and the plages, like flares, usually occur in association with sunspots.

It is known that magnetic activity in the earth's field varies with the sunspot cycle, although the exact relation between individual spots and magnetic storms remains obscure. Some magnetic disturbances, or "storms," occur when no very active solar region is visible, while the greatest sunspot ever observed in recent history, which was about six billion square miles in extent, produced no identifiable magnetic activity on earth. During parts of the sunspot cycle when activity is low, a twenty-seven day periodicity is noted in the minor magnetic disturbances of the earth's field, indicating a definite relationship between as yet unidentified regions on the sun, perhaps associated indirectly with sunspot groups, and the terrestrial effects.

The spots are under continuous surveillance by solar astronomers in a vigorous program and there is little need for augmentation of the observations during the IGY. Related to the daily observations of the spots, however, is the IGY International Flare Patrol, which is a program to observe and photograph the flares in the light of Hydrogen Alpha (6563A wavelength) for the purpose of maintaining a continuous study of the sun's activity and to secure information necessary to predict great magnetic storms and other terrestrial effects associated with solar outbursts. During the IGY, the magnetic fields of the sun will be studied in great detail at the Mount Wilson Observatory, with a special electronic instrument, developed by the Babcocks for observing Zeeman splitting, in an effort to learn as much as possible about the relationship of the magnetic field to various surface and chromospheric disturbances, such as sunspots and flares.

The IGY Research Rocket Program

In the United States, the rocket research of Robert Goddard, extending over nearly two decades, 1920 to 1940, helped pave the way for later rocket development. The German V-2 rocket developments of World War II provided a technologic basis for subsequent applications. The development of rockets specifically for upper-atmosphere research was undertaken in the United States by laboratories in the Department of Defense and associated universities. For example, there was the development of the Aerobee and the Viking and, more recently, techniques which carry rockets aloft by balloon before the actual rocket launching. High-atmosphere research rockets in the United States and elsewhere in recent years have yielded significant fundamental data and have established a foundation for new departures in upper-atmosphere research. The advances in the past decade or so have been so rapid, in fact, that the International Geophysical Year has seen the first earth satellite, set on orbit by a rocket.

Types of Rockets

The USNC-IGY rocket program includes the firing of some 194 rockets. In addition, twenty-nine pre-IGY test rockets were fired. Five types of rocket are being used:

The *Aerobee-Hi* is a liquid fuel rocket, using a mixture of nitric acid and alcohol. It carries a payload of 150 pounds in a four- to six-cubic-foot space to altitudes over 150 miles.

For certain experiments which do not require the very high altitude attained by the Aerobee-Hi, a standard *Aerobee* is used to carry a payload of 150 pounds to an altitude of about 60 miles.

The *Nike-Cajun* carries a payload of 40 pounds to an altitude of 100 miles and uses a solid propellant. The *Nike-Deacon*, or Dan, also uses a solid propellant to carry a payload of 40 pounds to an altitude of 75 miles. In both of these rocket systems, the Nike is used as a booster.

The *Rockoon* is a Deacon rocket carried to an altitude of 70,000 to 80,000 feet by a "Skyhook" balloon before the rocket is fired. It carries a payload of 40 pounds to an altitude of 60 miles.

Many rockets will carry out several experiments, so that the total number of rockets does not give an accurate picture of the scientific importance of this program. For example, there are three types of experiments involved in shipboard rockoon launchings from the Arctic to the Antarctic. In the first, rockoons carrying cosmic ray equipment will be launched about every five degrees of latitude in order to obtain a cross-section of cosmic ray intensity at various geomagnetic latitudes. In the second experiment, rockoons are to be sent into the ionosphere in the region of the geomagnetic equator to make direct observations of the presumed equatorial current. The third group of experiments involves the study of so-called soft radiation above 50 kilometers in the southern auroral zone. This will be coordinated with simultaneous observations in the northern auroral zone.

Launching Program

The major effort of the US-IGY rocket program will be centered at Fort Churchill, Canada, where an important new rocket launching installation has recently been completed through the cooperative efforts of the Canadian and US National Committees for IGY and the defense establishments of both countries. Other US rocket launching sites are at Holloman Air Force Base, New Mexico; White Sands, New Mexico; Pt. Mugu, California; Guam; and shipboard.

Table 1 shows IGY research rocket firings.

Rocket Experiments

Considerable technical ingenuity is required to devise measuring systems which can achieve their objectives without temperature, wind, and other distortions result-

ing from environmental factors caused by the rocket's own flight. Thus, an elaborate mechanism is required to provide a stable platform from which to obtain solar spectrographs aboard a spinning, yawing rocket. Atmospheric measurements must be protected from gasses exuded from the pores of the rocket's metal sides in high altitudes, surrounding it with an atmosphere of its own making.

A brief description of the rocket experiments follows:

Meteorology: Atmospheric structure—pressure, temperature, and density of the atmosphere at different levels—is determined by aerodynamic means from pressures measured at various positions on the rocket surface. Photon counters are used to measure solar X-ray penetration into the atmosphere, from which pressure in and above the E region of the ionosphere may be determined. Another experiment is based on the use of grenades which are ejected from the rockets and exploded in the upper atmosphere. By measuring the transit times of the sound waves from the exploded grenades, atmospheric temperatures and winds between 30 kilometers above the earth and the E region can be determined. Again, by measuring the drag on spheres ejected from a rocket the density of the D region of the ionosphere can be found. The optical horizon is located by means of high altitude photographs.

Solar Activity: During periods of marked solar activity, such as solar flares, particular efforts are made to study solar radiations and the sun's spectrum. Photon counters measure the solar radiations in various wavelengths, from the near ultraviolet to hard X-rays. Spectrographs and sunfollowers are used to study the sun's spectrum to wavelengths short enough to include the Lyman beta line of hydrogen.

Airglow: In the airglow experiments, photon counters are employed at various wavelength regions in the visible spectrum. Photomultiplier tubes and appropriate filters are also utilized. OH bands in the near infrared are measured.

Aurora: Geiger counters, proportional and scintillation counters, ionization chambers, and electrostatic analyzers are being used to measure auroral particles. The ultraviolet fluorescence of the atmosphere during the aurora is also being measured by rockets.

Ionospheric Physics: Three principal methods are used to determine ionospheric charge densities. In the first, the delay time of an electromagnetic pulse sent from the ground to a rocket and back is measured; the second uses a phase shift between two harmonically related signals transmitted from a rocket in the ionosphere to determine the index of refraction in the vicinity of the rocket; the third method seeks to determine charge densities from the effect of the ionosphere on DOVAP (Doppler, velocity, position) signals.

The distribution of ozone through the upper atmosphere is determined from rocket solar spectrographs. The chemical and ion composition of the high atmosphere is being studied by a radio frequency mass spectrometer.

Winds between the stratosphere and the E-region are determined through the ejection and explosion of grenades described above. There will also be an effort to determine atmospheric winds by aerodynamic measurements on the rockets themselves.

Geomagnetism: Both standard and proton precessional magnetometers are being employed to measure the earth's magnetic field. An attempt will be made to use these measurements to locate ionospheric and auroral current flows. The magnetometers will permit measurements of field strength within 10^{-4} gauss and component direction within a few degrees.

Cosmic Rays: Low-energy cosmic rays as a function of geomagnetic latitude are measured by geiger counters and ionization chambers and their fluctuation in intensity will be correlated with solar and magnetic phenomena.

TABLE 1

Location	Type & Number	Experiment	Instrumentation	Agency*
Churchill	Aerobee (33) Nike-Cajun (43)	Charge density in ionosphere	Doppler, velocity, and position (DOVAP); rocket borne pulse transmitter; rocket-borne CW transmitters	NRL; AFCRC
		Pressure, temperature, density	Ionization gauges	NRL; AFCRC
		Auroral particles and magnetic field	Proton precessional magnetometer; photo-multipliers, photon counters, and filters; particle counters and spectrometer	NRL
		Chemical and ion composition	Radio frequency mass spectrometer	NRL
		Horizon study	Camera	BRL
		Magnetic field electron density	Proton precessional magnetometer; DOVAP	BRL
		Water vapor	Infra-red hygrometer	BRL
		Density, temperature	Falling sphere	AFCRC
		Airglow	Scanning spectrophotometer	AFCRC
		Temperature, winds	Grenades, geophones; DOVAP	SEL
		Cosmic ray, auroral radiation and magnetic field	Proton precessional magnetometer; geiger counter and spectrometers; crystal counters; crystal counters and emulsions	SUI
Holloman	Aerobee (6)	Solar ultraviolet spectrum	Sunfollowing spectrograph	AFCRC
		Charge density in ionosphere	Rocket-borne pulse transmitter	AFCRC
		Dayglow	Scanning spectrophotometer	AFCRC
White Sands	Aerobee (3) Nike-Cajun (2)	Charge density and water vapor	Infra-red hygrometer; DOVAP	BRL
		Charge density and magnetic field	DOVAP	BRL
		Solar ultraviolet spectrum	Sunfollowing spectrograph	NRL
Pt. Mugu	Nike-Deacon (14)	Solar ultraviolet and X-ray during flares	Photon counters and ionization chambers	NRL
Guam	Nike-Cajun (8)	Temperature, winds	Grenades, geophones; DOVAP	SEL
Shipboard	Rockoon (85)	Soft particle radiation; cosmic ray intensity, magnetic field	Geiger counters and spectrometers	SUI

* *Agency Code:* AFCRC = Air Force Cambridge Research Center. BRL = Ballistic Research Laboratory. NRL = Naval Research Laboratory. SEL = Army Signal Engineering Laboratory. SUI = State University of Iowa.

Pre-IGY Rocket Firings

The US-IGY rocket program has been brought to a high state of readiness through enormous effort on the part of the scientists, technicians, military personnel, and laboratories involved in the program.

During the summer and fall of 1956, pre-IGY rocket firings were conducted by participating agencies. These firings, to test the rockets, their experiments, launching facilities, and general operations at the sites selected for use during IGY, took place at the White Sands Proving Ground, in the Pacific Ocean off San Diego, California, in the North Atlantic Ocean, and at Fort Churchill, Manitoba, Canada.

The rocket firings at Fort Churchill, Canada, represented the major effort. However, the other pre-IGY firings were vitally important to the program and are reported briefly below:

Seventeen rocket firings took place at loca-

tions other than Churchill; ten Rockoon firings were made from a vessel of the U. S. Navy stationed off the coast of San Diego, California. The firings were conducted by the Naval Research Laboratory July 17–27, 1956. Each Deacon rocket carried solar ultraviolet and X-ray detectors.

Two Nike-Cajun rockets were fired at the White Sands Proving Ground during August 1956. One was instrumented for the study of pressure, temperature, and density by the University of Michigan for the Air Force Cambridge Research Center. The second was instrumented by the Ballistic Research Laboratories for the study of charge density in the upper atmosphere. Both rockets were also tests of the new Nike-Cajun two-stage rocket research vehicle. Each of the firings was a success; the rockets reached predicted altitudes in the range of 90 to 100 miles, and the desired information was obtained on the performance of the prototype instrumentations.

Five Nike-Cajun rockets were fired from shipboard between the East coast of the United States and Greenland in the fall of 1956. These rockets contained the falling sphere experiment for the measurement of atmospheric density. This experiment was prepared for the Air Force Cambridge Research Center by the University of Michigan, and is an exact prototype of the one to be flown during the IGY at Fort Churchill.

At Churchill, rocket firings required the installation of complete range and launching facilities. The launching complex itself consisted of an Aerobee tower, movable 10° in any direction to compensate for winds, a building to house the Nike-Cajun (or Dan) launcher, preparation buildings, telemetering trailers, a blockhouse, a generator building, a helium building, and connecting tunnels.

Installed at various places throughout the military reservation at Fort Churchill were numerous instrumentation sites. Included were a five-station DOVAP system and ballistic cameras, installed and operated under the direction of the Ballistics Research Laboratory; two telemetering trailers and an ionosphere station installed and operated under the direction of the Naval Research Laboratory with the assistance of personnel of the New Mexico College of Agriculture and Mechanic Arts; and a network of sound ranging geophones installed and operated by the Army Signal Engineering Laboratory. Also included, installed and operated under the supervision of the White Sands Signal Corps Agency, were two radars, range safety plotting boards and a command transmitter, a frequency monitoring station, a timing system, meteorological and wind ballistic balloon launching facilities and sites, and a complete range communication system.

The pre-IGY rocket program was highly successful from both rocket and instrumentation standpoints; the experience gained will contribute substantially to IGY efforts. The entire program itself was made possible only through the help and cooperation of the Department of Defense, and, in the case of Fort Churchill, the Canadian Government. The program has been materially aided by the Special Committee for the IGY (SCIGY) of the Upper Atmosphere Rocket Research Panel; this is also the operational working group of the USNC Technical Panel on Rocketry, as the three-service, Army, Navy, and Air Force, cooperative effort.

IGY Antarctic Weather Central

The establishment and maintenance, by the US National Committee, of an IGY Antarctic Weather Central to collect and disseminate Southern Hemisphere weather information, particularly for the Antarctic region, was recommended and approved at the First CSAGI Antarctic Conference, held in Paris, July 6–10, 1955.

The basic program at Weather Central involves the reception and recording of weather data from many contributing sources; preparation and analysis of meteorological charts, maps, graphs, and cross sections—mostly synoptic; and broadcasting of current weather information and analyses for forecasting use by stations throughout Antarctica and the remainder of the Southern Hemisphere. Research and training programs are also included, especially during the Antarctic winter months when the general decrease in field activity limits the need for forecasting. In addition, Antarctic Weather Central analyses will be co-ordinated with the IGY World Weather Map series.

Facilities for the Weather Central were fully installed by February 1957 in the meteorology building at IGY Little America Station. At present, the Weather Central staff consists of four US meteorologists and one each from Argentina and the USSR. These participate equally in the program, sharing in the shift work, assisting in processing data, preparing charts and maps, and making analyses and forecasts.

The staff will be increased from six to seven for the next Antarctic winter—three from the US and one each from Argentina, Australia, France, and the USSR. Three additional meteorologists, one each from Belgium, South Africa, and the US, will be added during the Antarctic summer of 1957–1958.

The meteorological information obtained from reporting stations includes standard surface data and upper-air observations from rawinsonde, radiosonde, and pilot balloon ascents. Most Antarctic weather information is received by manual CW radio at the Williams Air Operations Facility, at McMurdo Sound about 400 miles to the east, and transmitted to Weather Central by radioteletype. In order to minimize man-made interference at Little America and to improve capabilities for reception of international weather broadcasts from South Africa, South America, Australia, and New Zealand, the transmitters for the Antarctic mother-daughter communications network and for the US and New Zealand circuits were installed at McMurdo. The circuit between Little America and McMurdo has been reported quite reliable on a 24-hour basis.

Weather data reaches Weather Central daily from all mother stations. Reports from the Australian-IGY Mawson Station are transmitted to the USSR-IGY Mirny Station, for relay to Weather Central. Mirny also relays data from the Kerguelen Island Station (Fr.). Weather reports from Australia and New Zealand arrive via standard international meteorological broadcasts. Reception of similar broadcasts from South Africa and South America has not come up to expectations although South African data is received sporadically by relay from Mirny, and South American reports are received through the O'Higgins (Chile) and Decepcion (Arg.) Stations. Work is being done to improve communications with the Norwegian stations and the Japanese Showa Station.

Meteorological information is also received in the summer season from whaling vessels, and from IGY expedition ships, aircraft, and travelling parties.

Incoming data are utilized, four times daily at present, for the preparation of sea-level charts of Antarctica and surrounding oceanic areas up to 50°S. Charts of the 700-, 500-, and 300-mb levels are analyzed twice a day. Statistical extrapolations from surface charts are being relied upon rather than thickness charts, to give upper-air heights over ocean areas. Adiabatic charts are plotted twice daily for each of the 16 Antarctic upper-air stations, and nine time cross-sections are prepared and analyzed. Continental weather summaries and 24-hour weather outlooks are also issued. Completed analyses and outlooks are compared and correlated with those issued by meteorological stations in Australia, New Zealand, and South Africa, thus obtaining a more complete picture of Southern Hemisphere atmospheric circulation.

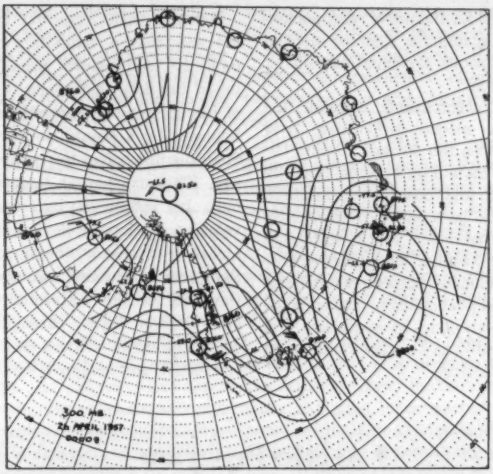

FIG. 2. *Atmospheric circulation at the 300-mb level over Antarctica at 0000 GMT, April 26, 1957, based on Weather Central data. Heights are in meters above sea level; temperatures are in degrees Centigrade; arrows fly with the wind and wind speed is shown by one full barb for each 10 knots per hour and a filled-in flag for 50 knots.*

Weather Central outlooks are used by meteorologists at the various Antarctic stations as background for on-the-spot local forecasting. Weather Central itself does no forecasting except for a recently begun terminal forecasting program for Little America Station; some regional and route forecasts for scheduled air, sea, and ground operations, as well as for emergency operations, are also made. The Byrd and South Pole Stations have been asked to transmit terminal forecasts, beginning about September 1.

The Weather Central broadcast schedule comprises four weather collective broadcasts daily, at 0415, 1015, 1615, and 2215 GMT, but until recently, all Weather Central analyses have been delayed 24 hours owing to irregular or too infrequent transmission of data from the contributing stations. Transmission schedules are improving, however, and it was expected that by early September, Weather Central would be able to broadcast its analyses about 12 hours after synoptic map time. Weather Central information and analyses are re-broadcast four times daily by the Mirny Station to ensure adequate coverage in the African quadrant of the Southern Hemisphere.

Microfilming of all Weather Central scientific data and records, in order to make a compact, permanent record of them, is now in progress.

During the winter months, when more time is available owing to slackening of activity throughout Antarctica, all IGY Antarctic Weather Central personnel conduct empirical studies to improve understanding of the large- and small-scale features of the Antarctic atmospheric circulation and to attempt to develop improved analysis and forecasting techniques. These studies include weekly discussions, recorded on tape, of synoptic patterns, weather, and analyses, as well as preparation of 10-day and monthly mean charts for meteorological parameters. All notes and conclusions resulting from these studies will be incorpo-

rated in a manual for the use of relief personnel the following summer, and for meteorologists of all nations participating in IGY Antarctic research.

Early IGY observations suggest the existence of a second tropopause over Antarctica between the 50- and 20-mb (19–20 km) levels. This will be watched carefully for confirmation and possible explanation. Evidence has also been gathered apparently confirming the tendency for a deep cold cyclone to exist at high levels above Antarctica, a previously suspected but not directly observed phenomenon. The cyclone, however, appears not to be stationary and evinces considerable day-to-day variation in location and intensity.

Records from Antarctic icecap stations indicate that a temporary rise in mean monthly temperatures usually follows the initial big drop that comes with the setting of the sun for the Antarctic winter. This is followed by a steady decrease, reaching a final low just before the reappearance of the sun. This unexpected temperature regime may be influenced by cloudiness, wind velocity, the large-scale circulation, or combinations of these or other factors. It is hoped that firm conclusions may be drawn after the end of the Antarctic winter, when observations taken throughout the full season at many stations can be compared, correlated, and analyzed.

Arctic Program

The US-IGY Arctic program includes projects in virtually all scientific disciplines to be studied during the IGY. Observations and experiments are being conducted in solar activity, cosmic rays, ionospheric physics, aurora, geomagnetism, meteorology, glaciology, oceanography, seismology and gravity. Most studies are synoptic in nature, their results ultimately to be compared and correlated with those obtained at stations throughout the rest of the world, particularly in Antarctica.

About 50 US stations, distributed over approximately 150 degrees of longitude, have been established in the Arctic. In addition, aircraft are employed to make some measurements, particularly in meteorology, and instrument-carrying rockets, fired from Fort Churchill, Manitoba, in cooperation with the Canadian National Committee, and from ships in northern waters, are probing the upper atmosphere.

(*A report of the scientific programs in progress on the two US-IGY drifting stations in the Arctic Ocean appeared in the July issue of the Bulletin on page 617.*)

Aurora

Most IGY auroral observations were scheduled to begin in September 1957, after the onset of the long Arctic night. The two principal objectives of the program are an accurate delineation of the northern auroral zones, along with a determination of the periodic variations within these zones, and studies of auroral physics.

The all-sky camera—which utilizes a convex mirror to photograph the entire sky during auroral displays—and auroral radar, are the instruments primarily used to establish the position in space of aurorae. At any given location, the photographic record furnishes information on the type, motion, and integrated intensity of auroral forms as a function of local time. Synoptic maps are being constructed, based on this photographic data; they will indicate the distribution and movement of the auroral forms. All-sky camera installation sites are at Barrow, Bettles, College, Fort Yukon, Farewell, Northway, and Kotzebue, Alaska; Aklavik (tentative), and Knob Lake, Can-

ada; Thule, Greenland; Drifting Station A and Fletcher's Ice Island.

A chain of auroral radar stations is being established along meridional lines in Alaska in order to measure the latitude shift in the auroral zone during displays. Specific locations are Barrow, College, King Salmon, Kotzebue, and Unalaska. Operation was to begin prior to the equinoctial period of maximum auroral activity. Unlike the all-sky camera, radar is not limited by weather and light conditions.

A profile of spectral features of aurorae along a meridional line, showing the production of auroral luminosity of the atmosphere by primary protons, will be obtained by use of patrol spectrographs at College, Alaska; Drifting Station A; Thule, Greenland; Saskatoon, Canada; and other stations outside the Arctic region. A scanning spectrometer at College is expected to provide information on the rapid changes of the auroral spectrum during periods of high geomagnetic activity. Riometers, recently designed to make high-accuracy continuous measurements of the relative ionospheric opacity, using the cosmic noise method, have been installed at College, Barrow, Farewell, Ft. Yukon, King Salmon, and Unalaska, Alaska; Knob Lake and Meanook, Canada; Thule, Greenland; and Kiruna, Sweden.

Cosmic Rays

The IGY program for cosmic ray study involves exploration of the variations in mass and energy of the primary spectrum of cosmic radiation and recording of variations in cosmic radiation intensity at the surface and at altitude. Because the low-energy cosmic rays can reach the earth's atmosphere in the region of the magnetic poles, many cosmic ray studies must be conducted in Arctic and Antarctic areas. The relation of low-energy cosmic ray primaries to high-energy auroral primaries particularly warrants study.

Comparison of cosmic ray data from both polar regions provides information on the isotropy of cosmic rays in space and the character of the geomagnetic field at great distances from the earth. Recent findings suggest the possibility of an asymmetry between Arctic and Antarctic cosmic-ray data.

In connection with the cosmic ray program, a neutron monitor telescope has been installed at College, Alaska, and is now in continuous operation. A second neutron monitor is under construction for installation at Thule, Greenland. A meson telescope, also to be used at Thule, has been shipped and is expected to be installed and in operation shortly.

Balloon flights from Thule will be conducted as part of a program to investigate the latitude effect, fluctuations in the primary radiation in equatorial regions compared with those at high latitude, and the general picture of cosmic ray phenomena at high altitudes at this phase of the solar cycle compared with other phases. During the balloon flights, supplementary ground observations with the meson telescope and geiger counters will be made at the launching sites and at intermediate positions. Long-duration balloon flights from Manitoba will measure fluctuations in primary cosmic-ray intensity. Photographic emulsions carried by balloons will be exposed at high altitudes to collect data on the energy range of the primaries and the nuclear reactions they induce.

The unusually long path traversed by solar radiation in the Arctic, similar in length to sunrise-sunset paths in lower latitudes, provides ideal conditions for solar infrared absorption measurements. Such measurements will be made at Thule during the long summer daylight hours. Analysis of the spectra obtained will provide information on the atmospheric concentration of CO, CH_4, CO_2, and other minor constituents in polar regions.

Ionospheric Physics

The Arctic ionosphere is a highly complex region in which the normal ionic layers are

constantly disturbed and distorted by strong atmospheric turbulence, auroral currents, and appreciable fluxes of incoming particles. An understanding of the nature of these motions and an adequate description of the polar ionosphere are lacking. Because the day-night cycle, complete in 24 hours elsewhere, requires 12 months near the pole, the study of the polar upper atmosphere offers the solution to many ionospheric mechanisms, permitting detailed study of the rate of absorption of electrons during the long polar nights, and the rate of ionization during the polar day.

Ionospheric soundings during the IGY will also provide information on the equivalence of ionospheric characteristics in the two polar regions, and on the three-dimensional form of the earth's magnetic field. The new IGY station at Thule, Greenland, less than 2° from the north geomagnetic pole, has already obtained many soundings verifying the conventional picture of a vertical magnetic field at great heights over the geomagnetic pole.

In the US-IGY Arctic program, vertical incidence soundings using standard sweep-frequency equipment (1 to 25 mc/sec in 15 seconds) are being made at Adak, Anchorage, College, and Barrow, Alaska; on Fletcher's Ice Island; in cooperation with Denmark, at Thule, Narsarssuak, and Godhavn, Greenland; and, also cooperatively, at Reykjavik, Iceland. A fixed-frequency backscatter instrument at College has been in operation for several months, and similar equipment at Thule, and at Knob Lake and Meanook, Canada, began operation by July 1, 1957. A sweep-frequency backscatter station at Knob Lake begins operating in the fall of 1957.

During the IGY, twelve Arctic transits will be made by airborne recorders. Virtual height measured against frequency reflections will be continuously obtained. Later analysis will give a determination of the drift direction of the ionosphere. Wherever possible, the aircraft will fly over ground-based vertical incidence sounding stations.

Whistlers, radio signals of descending pitch initiated by lightning discharges and developed by dispersive propagation of sferics over very long extra-atmospheric paths, are being studied synoptically by a network of US-IGY stations in Arctic areas and elsewhere in the Western Hemisphere. Equipment is already installed and operating at Arctic stations at Anchorage, Unalaska, and College, Alaska, and at Knob Lake, Canada; additional stations are planned for Nome or Kotzebue, Alaska; Godhavn, Greenland; and Father Point and Frobisher Bay, Canada.

Radio noise recording equipment at Thule was expected to be in operation by August 1957. These studies of the naturally occurring radio signal pulses arising from lightning discharges will provide additional information about the characteristics of the ionosphere, as well as about thunderstorm incidence.

Geomagnetism

The main emphasis of the IGY geomagnetic program is on a series of observations and experiments designed to yield data on the rapid fluctuations of the earth's magnetic field. These variations, which make up a relatively small part of the earth's generally stable magnetic field are most frequent and strongest in polar and equatorial regions; a large part of the IGY effort in these studies is, therefore, being made in the Arctic. As one of the three hypothetical great upper atmosphere electrical currents that give rise to these fluctuations coincides with the northern zone of maximum auroral frequency, a network of stations has been established in Alaska transecting this zone. Surface magnetic data will be supplemented by data from rockets and earth satellites, by radio wave propagation data, and by data from ionospheric, auroral, and solar observations.

Five Alaska stations—at Sitka, College, Point Barrow, Healy, and Big Delta—and two sets of sub-stations, or slave stations, attached to the College station are now

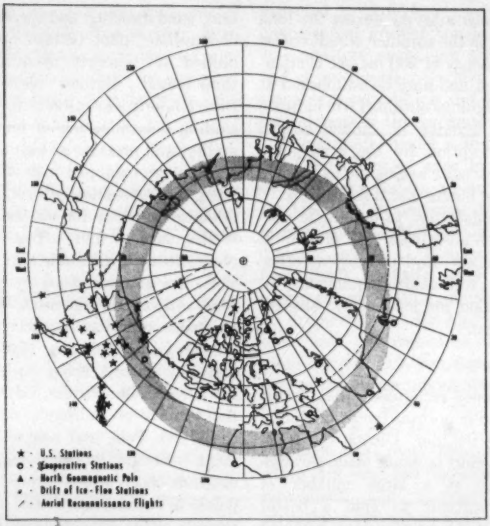
E of E
E of E
★ - U.S. Stations
○ - Cooperative Stations
▲ - North Geomagnetic Pole
✈ - Drift of Ice - Flow Stations
✈ - Aerial Reconnaissance Flights

FIG. 3. *US-IGY Arctic Region Stations. Dark band is zone of maximum occurrence of auroras. Path of reconnaissance flights is sometimes varied or reversed to obtain wider coverage or to adjust to changes in weather conditions.*

equipped with Ruska rapid-run magnetographs and standard magnetographs of normal and low sensitivity; all have begun operations. The Healy, Big Delta, and two of the satellite stations are new; the others were operating prior to the IGY.

The College station is also operating a newly devised differential magnetograph. This consists of a central recording instrument at the U.S. Coast and Geodetic Survey observatory, near Fairbanks, connected by electrical cable to instruments at two slave stations about 7 miles away in the magnetic south and west directions. Measurements obtained will make it possible to compute the intensity and location of the ionospheric electrical currents that are presumed to be responsible for disturbances in the magnetic field.

Askania 3-component variographs are in operation at all stations of the north-south trans-auroral Alaska network and on Drifting Station A. The network, consisting of stations at Anchorage, Kotzebue, Northway, Fort Yukon, and Barter Island, will provide information about ionospheric currents affecting the local geomagnetic field. A transit magnetometer, fitted with a deflection magnet for H observations, will be installed on Drifting Station A.

Visual magnetic variometers will be installed at Barrow and College, Alaska, and at Thule, Greenland, to provide hour-by-hour information on disturbances in the magnetic field. Thule and College will also receive instrumentation to record magnetic fluctuations in the 1- to 50-cycle frequency range. The measurements will be compared with similar data obtained in middle latitudes.

Solar Activity

Tentative IGY plans are to establish a station at College, Alaska, for continuous

monitoring of solar activity during the long polar day. During the summer, a radio noise patrol at a frequency of 200 mc/sec is maintained at College, and may be established at other sites. Recordings obtained will indicate the onset and severity of sudden cosmic radio noise absorption by the earth's atmosphere. At low solar angles the patrol will be principally of bursts and noise storms.

Indirect flare detectors to determine sudden cosmic noise absorption will also be in operation at College, and possibly at other locations; they will utilize equipment already in operation for ionospheric absorption measurements.

Meteorology

It has long been recognized that Arctic air masses are an important factor in Northern Hemisphere weather. During the IGY, a concentrated effort is being made through synoptic studies at a large number of meteorological stations to gain a better understanding of the relationships involved among the various factors that make up our weather. Many new stations have been established, especially in polar areas, where the need is greatest, and stations in existence prior to IGY have been improved by addition of new types of equipment.

There are some 18 meteorological stations in Alaska as a part of the IGY Arctic meteorological program; most of them are permanent stations established prior to IGY. Additional stations have been installed on Drifting Stations A and B (the latter on Fletcher's Ice Island) in the Arctic Ocean, and about eight more have been established in Canada and Greenland and are being operated on a cooperative basis. The stations at Thule, Greenland, and the Alert, Eureka, Ft. Churchill, and Resolute stations, in Canada, constitute the northern end of the 70° to 80° W pole-to-pole chain of meteorological stations.

Standard meteorological observations are being made at most Arctic stations. These include continuous recording of surface temperature, humidity, pressure, precipitation, wind direction and speed, and duration of sunshine; pilot balloon observations, as needed for aircraft operations; standard three-hourly surface observations; and twelve-hourly rawinsonde observations, including determination of temperature, humidity, and pressure at high altitudes. Most stations are equipped with newly developed 800-gm rawinsonde balloons, with a height potential of about 100,000 feet.

The surface and high-altitude balloon observations being made at most Arctic stations are supplemented by meteorological observations from aircraft. Weather reconnaissance observations, along the 700-mb (10,000 ft) and 500-mb (18,000 ft) pressure surfaces, are now being made on flights by the Air Weather Service, US Air Force, from the vicinity of Fairbanks to a point near the North Pole, and return. The measurement schedule includes standard meteorological observations every half hour at points over the Arctic Ocean, and dropsonde releases at five points along the flight path. Meteorological elements reported are visibility, weather, turbulence, cloud conditions, temperature, dew point, height of pressure surface, surface and upper-air wind, icing rate, condensation trails, and surface ice.

In connection with meteorological heat and water budget studies, closely linked with related studies in oceanography and glaciology, personnel at Drifting Station A are also making observations of solar radiation, reflectivity of the snow surface, net radiation heat flux, sky brightness, total atmospheric ozone (with a Dobson spectrophotometer), and vertical wind and temperature structure near the ground and, with a wire-sonde, up to a height of 1000 feet. A Dobson spectrophotometer is also in use at the College Station. Six Alaskan stations, including College and Drifting Station A, are also making solar radiation measurements, using the Eppley pyrheliometer.

One early result of IGY Arctic meteorological studies has been the observation by some stations of several instances of high-level warming. Temperature increases from

−80° to −15° C at the 25-mb level, occurring within a period of three of four days, have been noted. Preliminary analysis suggests that this phenomenon is probably caused by large-scale subsidence in the atmosphere.

Oceanography

In addition to the many special studies being conducted on the drifting stations, standard measurements of long period waves, sea level variations, and steric observations are being made at fixed stations at Adak, Attu, Barter Island, Kodiak, Point Barrow, and Unalaska, Alaska, and at Thule, Greenland.

The dynamics of Arctic sea-ice movement, as well as seasonal changes in volume, are being studied by aerial reconnaissance. A number of flights have been made, and under present plans flights are to be made at two-week intervals from March through September 1957, and March through September 1958, usually in conjunction with weather reconnaissance observations by the US Air Force Air Weather Service. Photographic records are being obtained.

A synoptic deep water survey of part of the North Pacific Current, being undertaken this summer by ships of the US, Japan, Canada, and the USSR will include northern waters up to the Aleutians. In the summer of 1958, a longitudinal profile survey to be made by US and Canadian ships will include bathymetry, bottom sampling, and physical and chemical studies as far north as Bering Strait. Particular attention will be given to the deeper waters, below about 8000 feet.

Glaciology

Arctic glaciology during the IGY is concerned with the morphology, history, and mechanics of mountain glaciers, ice sheets, and drift ice, and with the influence of this great volume of polar ice on the meteorology, climatology, and oceanography of the remainder of the northern hemisphere. Synoptic studies of the fluctuations in mass of northern glaciers and Arctic sea-ice are expected to provide clues to past climatic changes and present trends. Study of heat and moisture exchanges across the sea-ice and air-ice interfaces, and of long-range and seasonal accumulation and ablation, are essential parts of this program.

The McCall Glacier in the Brooks Range, the Lemon Glacier, near Juneau, and parts of the Alaska Range, are now being studied by US-IGY glaciological teams. Work in progress on the McCall Glacier, under the direction of R. C. Hubley, represents the first direct scientific study of an Arctic alpine glacier. With equipment and supplies air dropped by the US Air Force, two camps have been established on the glacier. The main camp is in a firn region on the upper part of the glacier, about 8200 feet above sea level, and the second camp is about a mile above the glacier terminus, at an elevation of about 6000 feet. Two men at the high camp are engaged in snow stratigraphy, movement, and micrometeorological observations; two others at the lower camp are conducting surface movement observations and photogrammetric studies. A recent report from the project leader states that it has become clear that all significant snow accumulation on these glaciers occurs during the summer months.

Special IGY glaciological studies are being made on the great continental ice sheet of Greenland by the Snow, Ice, and Permafrost Research Establishment (SIPRE) of the Corps of Engineers, US Army. A 1700-foot drillhole in the ice sheet has shown a temperature gradient of only 0.5°F per 1000 feet, from 24.5° to 25.0°. Such deep holes give further information on the temperature gradient of the ice and on the rate of closing of the hole.

Seismology and Gravity

The US-IGY Arctic programs in seismology and gravity are part of the worldwide IGY effort to gather information on the precise shape, or figure, of the earth; on earth tides; on the structure and seismicity of both the crust and interior of the earth; and on

related phenomena. Sufficient observations and measurements in these disciplines have heretofore been lacking for the polar regions. Accurate determination of the oblateness of the geoid, and the distortion near the geographic North Pole can be made from accurate gravity measurements in the Arctic.

Arctic gravity and seismic measurements will also help greatly in working out the geologic structure of the Arctic Basin. A 10,000-foot submarine mountain range, the Lomonosov ridge, has already been outlined by bathymetric measurements made from ice-floe bases by Soviet scientists, and, separately, by US scientists on Fletcher's Ice Island. More recently, US scientists conducting gravity investigations on Drifting Station A have discovered a 5000-foot submarine ridge paralleling the Lomonosov ridge.

During the IGY, gravity standardization measurements to increase coverage by reliable gravity stations and to provide a number of additional first-order control points for local gravimeter surveys are being made along north-south lines with the Gulf compound quartz pendulum. Pre-IGY measurements in this program have already been made between Fairbanks, Alaska, and Paso Cortez, Mexico. Thule, Greenland, is the northern station of another line extending down the eastern coasts of North and South America to Cape Horn. Still another north-south line of stations will connect the Aleutians with Antarctica, by way of the east coast of Asia and through Australia. The quartz pendulum measurements at these sites will be complemented by measurements with Cambridge University compound, magnetically-compensated Invar pendulums. Pendulum measurements are also to be made at Barrow and Barter Island, Alaska, and cooperatively at the Canadian stations at Alert, Eureka, Mould Bay, and Resolute.

Pendulum ties have already been made to the two Arctic Ocean drifting stations. Throughout their occupation, essentially driftless gravimeters, such as the Frost meter —a zero length spring-type instrument—will be read daily. There will be close coordination between gravity work on the drifting stations and the Geophysical Research Directorate program of oceanographic studies.

Earth tide measurements, which provide a basis for determining the rigidity of the earth's crust and add to our knowledge of the nature and structure of its interior, are to be made for a period of 31 days at the Barrow station.

These observations will be analysed in conjunction with similar determinations by other polar stations.

As part of the US-IGY program, a standard seismographic station has been established at Thule, Greenland. The Thule station is equipped with both vertical and horizontal component instruments. Standard stations at College and Sitka, operated by the Coast and Geodetic Survey, are also supplying seismic data. Observations from these sites will permit more precise determinations of earthquake locations, both within the Arctic and throughout the remainder of the world.

In cooperation with Canada, a long-period seismograph, to be operated by resident personnel, is to be installed at Resolute Bay Station. Dispersion of surface waves over the continents and oceans will be measured.

Arctic stations are also observing microseisms, small crustal vibrations attributed to storms over the oceans or near their borders. Study of the relationship between Arctic microseisms and Arctic and North Atlantic meteorology and oceanography is part of this aspect of the seismology program.

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Stability of the Motion of a Rotating Axial Symmetrical Solid Body in a Fluid*

SHIH-KUNG KAO

Abstract—The stability criterion of the motion of an axial symmetrical solid body rotating about its axis of revolution and moving in the direction perpendicular to its axis of rotation is obtained. The major controlling factors which stabilize a rotating top in a fluid are examined. For a flat circular top ($A < B$) the stabilizing effect of rotation appears less effective in the case of the rotating top translating in the direction perpendicular to the axis of rotation than parallel to the axis of rotation; the translation velocity destabilizes the rotating top in the former case but stabilizes it in the latter case.

It may be because of the practical interest of the dynamic characteristics of flight of elongated projectile from rifling, or the relatively simple formulation of the dynamical system, that the problem of the stability of the motion of solid in a fluid moving along and rotating about its axis of revolution was investigated by *Greenhill* [1879]. The question of the stability of the motion of a solid body rotating about its axis of revolution and moving in a direction perpendicular to it, and of the motion of a solid body rotating about and moving along an axis perpendicular to its axis of revolution seem not to have been studied. Indeed the problem of the former, in some respects, resembles the motion of a satellite or a flying saucer. To examine the major controlling factors which stabilize a rotating top moving in a fluid is the purpose of this note.

Let the z axis of a cartesian coordinate system, which is moving and rotating with the solid, coincide with the axis of revolution of the solid; the x and the y axes are in the plane of symmetry which is of course perpendicular to the axis of revolution of the solid. Denote in this coordinate system the angular velocity and velocity vector, respectively, by

$$\Omega = \Omega_1 i + \Omega_2 j + \Omega_3 k$$

and

$$V = V_1 i + V_2 j + V_3 k$$

i, j, k being unit vectors, Ω_1, Ω_2, Ω_3 the components of angular velocity, and V_1, V_2, V_3 the velocity components in the x, y, z axes respectively.

The kinetic energy of this system may be expressed by

$$2T = A(V_1^2 + V_2^2) + BV_3^2 + P(\Omega_1^2 + \Omega_2^2) + Q\Omega_3^2 \quad (1)$$

where A, B, P and Q are constants roughly corresponding to axial moments of inertia determined by the shape of the solid of revolution. From the above equation of kinetic energy we obtain the impulsive force, and the impulsive couple respectively

$$\xi = AV_1 i + AV_2 j + BV_3 k \quad (2)$$

and

$$\lambda = P\Omega_1 i + P\Omega_2 j + Q\Omega_3 k \quad (3)$$

Let us consider first the stability of the motion of a solid body rotating about its axis of revolution but moving in a direction perpendicular to it. Let the constant angular velocity and translation velocity of the solid body be Ω and U respectively. We have

$$\begin{aligned} \Omega_1 &= \omega_1, \quad \Omega_2 = \omega_2, \quad \Omega_3 = \Omega + \omega_3 \\ V_1 &= U\cos(\Omega_3 t + \delta) + u_1 \\ V_2 &= -U\sin(\Omega_3 t + \delta) + u_2 \\ V_3 &= u_3 \end{aligned} \quad (4)$$

where ω_1, ω_2, ω_3 are perturbation components of angular velocity; u_1, u_2, u_3 perturbation velocity components; δ is the angle made from the direc-

* Contribution from Meteorology Department, University of California, Los Angeles, No. 33.

tion of U to the x axis at the time the motion of the solid is disturbed.

To satisfy Euler's dynamic equations [for example, *Milne-Thomson*, p. 470, 1949]

$$d\xi/dt + \Omega \times \xi = 0 \tag{5}$$

and

$$d\lambda/dt + \Omega \times \lambda + V \times \xi = 0 \tag{6}$$

We obtain for this dynamic system

$$du_1/dt - \Omega u_2 - Ut \sin(\Omega_3 t + \delta)\cdot d\omega_2/dt = 0 \tag{7}$$

$$du_2/dt + \Omega u_1 - Ut \cos(\Omega_3 t + \delta)\cdot d\omega_2/dt = 0 \tag{8}$$

$$\gamma du_3/dt - \sin(\Omega_3 t + \delta)\omega_1 - \cos(\Omega_3 t + \delta)\omega_2 = 0 \tag{9}$$

$$d\omega_1/dt - \alpha\omega_2 + \beta \sin(\Omega_3 t + \delta)u_3 = 0 \tag{10}$$

$$d\omega_2/dt + \alpha\omega_1 + \beta \cos(\Omega_3 t + \delta)u_3 = 0 \tag{11}$$

$$d\omega_3/dt = 0 \tag{12}$$

where

$$\alpha = (1 - Q/P)\Omega, \quad \beta = (A - B)U/P, \quad \gamma = B/AU$$

To determine the stability criterion of the motion of the rotating top we shall examine the characteristics of the above system of differential equations with variable coefficients. The differential equations for u_1 and u_2 can easily be obtained from (7), (8), and (12)

$$d^2u_1/dt^2 + \Omega^2 u_1 = 0$$

$$d^2u_2/dt^2 + \Omega^2 u_2 = 0$$

Thus u_1 and u_2 are sinusoidal functions depending only on the constant angular velocity Ω. Eq. (12) shows that ω_3 is a constant, thus Ω_3 is a constant and we may for simplicity denote it by Ω.

Eliminating the terms containing u_3 from (10) and (11), then making use of (9) we can show that

$$\gamma(\Omega - \alpha)\frac{du_3}{dt} + \frac{d}{dt}\{\omega_1 \cos(\Omega t + \delta) - \omega_2 \sin(\Omega t + \delta)\} = 0 \tag{13}$$

Integration of the above differential equation gives

$$u_3(t) = \frac{1}{\gamma(\Omega - \alpha)} \cdot \{\omega_1(t) \cos(\Omega t + \delta) - \omega_2(t) \sin(\Omega t + \delta)\} + H \tag{14}$$

where

$$H = u_3(0) - \frac{1}{\gamma(\Omega - \alpha)}\{\omega_1(0) \cos\delta - \omega_2(0) \sin\delta\}$$

$u_3(0)$, $\omega_1(0)$ and $\omega_2(0)$ are the initial values of u_3, ω_1 and ω_2 respectively.

Eliminating the terms containing ω_1 and ω_2 from (7) and (8), then

$$\beta\gamma \frac{du_3^2}{dt} + \frac{d}{dt}(\omega_1^2 + \omega_2^2) = 0 \tag{16}$$

Integration of (16) gives

$$u_3^2(t) = -(1/\beta\gamma)(\omega_1^2 + \omega_2^2) + G \tag{17}$$

where

$$G = u_3^2(0) + (1/\beta\gamma)\{\omega_1^2(0) + \omega_2^2(0)\} \tag{18}$$

From (14), (17) and (9) we may eliminate the terms containing ω_1 and ω_2; the differential equation for u_3 becomes

$$\left(\frac{du_3}{dt}\right)^2 + \left\{\frac{\beta}{\gamma} + (\alpha - \Omega)^2\right\} \cdot \left\{u_3^2 - 2\frac{H\gamma(\alpha - \Omega)^2}{\beta + \gamma(\alpha - \Omega)^2}u_3 + \frac{\gamma(\alpha - \Omega)^2}{\beta + \gamma(\alpha - \Omega)^2} \cdot \left[H^2 + \frac{\beta G}{\gamma(\alpha - \Omega)^2}\right]\right\} = 0 \tag{19}$$

The above differential equation has a solution

$$u_3(t) = HR + E \cos\eta t \tag{20}$$

where

$$\eta = \left\{\frac{\beta}{\gamma} + (\alpha - \Omega)^2\right\}^{\frac{1}{2}}$$

$$R = \frac{\gamma(\alpha - \Omega)^2}{\beta + \gamma(\alpha - \Omega)^2}$$

$$E = \frac{1}{2}u_3(0) - \frac{1}{2}HR + \left\{[u_3(0) + HR]^2 + \frac{\beta R(HR - G)}{\gamma(\alpha - \Omega)^2}\right\}^{\frac{1}{2}} - \frac{\beta R(HR - G)}{2\gamma(\alpha - \Omega)^2\left[u_3(0) - HR + \left\{[u_3(0) + HR]^2 + \frac{\beta R(HR - G)}{\alpha(\alpha - \Omega)^2}\right\}^{\frac{1}{2}}\right]} \tag{21}$$

The condition that u_3 should be an oscillatory function is that η should be real, that is, provided

$$(A - B)\frac{A}{BP}U^2 + \frac{Q^2}{P^2}\Omega^2 > 0 \tag{22}$$

Since A, B, P and Q are positive constants depending only on the shape of the solid, (22) shows that rotation of the solid always stabilizes the system, whereas the sidewise translation velocity destabilizes or stabilizes the system depending respectively on whether A is smaller or greater than B. For the former case the shape of the solid corresponds to a flat circular top whereas for the latter case it corresponds to an elongated ellipsoid.

In order to prove that the stability criterion (22) for velocity perturbation along the principal axis of the solid also serves as the stability criterion for rotation perturbations, we proceed to find the differential equations for ω_1 and ω_2 in terms of u_3. These can easily be obtained by differentiating (10) and (11) with respect to time and then making use of (20), (10) and (11).

$$\frac{d^2\omega_1}{dt^2} + \alpha^2\omega_1 + \tfrac{1}{2}\beta E\{(\alpha+\Omega+\eta)\cos[(\Omega+\eta)t+\delta] + (\alpha+\Omega-\eta)\cos[(\Omega-\eta)t+\delta]\} + \beta HR(\alpha+\Omega) = 0 \tag{23}$$

$$\frac{d^2\omega_2}{dt^2} + \alpha^2\omega_2 - \tfrac{1}{2}\beta E\{(\alpha+\Omega+\eta)\sin[(\Omega+\eta)t+\delta] + (\alpha+\Omega-\eta)\sin[(\Omega-\eta)t+\delta]\} - \beta HR(\alpha+\Omega) = 0 \tag{24}$$

It can easily be shown that the solutions for ω_1 and ω_2 are sinusoidal functions of time if η is real, exponential functions of time if η is imaginary. Thus (22) is the stability criterion for both translation and rotation of the dynamic system. Note that a non-rotating axial symmetrical solid tends to turn its broad surface to the direction of motion.

Now let us consider the stability of the motion of a solid rotating about and moving along an axis perpendicular to its axis of revolution. Again denote the angular velocity and translation velocity of this solid body by Ω and U respectively. For this system we have

$$\left.\begin{aligned} V_1 &= U + u_1, \quad & V_2 &= u_2, \quad & V_3 &= u_3 \\ \Omega_1 &= \Omega + \omega_1, \quad & \Omega_2 &= \omega_2, \quad & \Omega_3 &= \omega_3 \end{aligned}\right\} \tag{25}$$

The dynamic equations (5) and (6) give

$$\frac{du_1}{dt} = 0, \qquad \frac{d\omega_1}{dt} = 0, \qquad \frac{d\omega_3}{dt} = 0 \tag{26}$$

$$A\frac{du_2}{dt} - B\Omega u_3 + AU\omega_3 = 0 \tag{27}$$

$$B\frac{du_3}{dt} + A\Omega u_2 - AU\omega_2 = 0 \tag{28}$$

$$\frac{d\omega_2}{dt} + \left(1 - \frac{Q}{P}\right)\Omega\omega_3 + (A-B)\frac{U}{P}u_3 = 0 \tag{29}$$

The differential equation for u_3 may be obtained by differentiating (28) with respect to time, then eliminating du_2/dt and $d\omega_2/dt$ by (27) and (29).

$$\frac{d^2u_3}{dt^2} + \left[\Omega^2 + (A-B)\frac{A}{BP}U^2\right]u_3 - \frac{AQ}{BP}U\omega_1 = 0 \tag{30}$$

Since ω_3 is a constant as shown by (26), solution for u_3 is sinusoidal function if

$$(A-B)\frac{A}{BP}U^2 + \Omega^2 > 0 \tag{31}$$

Examination of (27) and (29) shows that stability criterion (31) holds also for u_2 and ω_2. We are particularly concerned with the instability with respect to ω_2 since it means the change of orientation of the solid with respect to the direction of translation of the solid. Eq. (31) gives the similar result deduced from (22) for the case of non-rotating solid, that is, the solid tends to face its broadest surface to the direction of translation. However, for a rotating flat circular top

$$(A < B,\ P > Q)$$

with the same angular velocity and translational velocities, the stabilizing effect of Ω appears more effective in the case of the solid body rotating and translating in the same direction than when the two are perpendicular to each other. In other words, for these two cases the motion of the former may be stable but unstable in the latter.

To study the stability of the motion of a rotating top one must consider both the stability criterion for the motion of the rotating top moving perpendicular to its axis of revolution (22) and that for the motion in the direction of its axis of revolution. The criterion of stability of a rotating top moving in the direction of its axis of rotation [see *Lamb*, 1932, p. 178; notation of this paper the symbols A and B are the reverse of the Lamb's notation].

$$4(B-A)\frac{B}{AP}U^2 + \frac{Q^2}{P^2}\Omega^2 > 0 \tag{32}$$

Equation (32) shows that rotation of the solid always stabilizes the circular top, whereas the

axial translation velocity destabilizes or stabilizes the system depending respectively on A being greater or smaller than B. For the former case the shape of the solid corresponds to an elongated ellipsoid whereas for the latter case it corresponds to a flat circular top. Comparing (22) and (32) one finds that rotation always serves as a stabilizing agent since the rotation term is positive in both cases, whereas the translation velocity destabilizes the top in one case, stabilizes in the other depending on the sign of $(A - B)$. However, in order to achieve stability of the motion for both cases but with minimum rotation, a slightly flat circular top should be chosen. A flat circular top $(B > A > 0)$ is always stable in a motion rotating about and moving along the axis of revolution since in this case both the rotation and translation terms in (32) are positive. It becomes unstable if the top moves in a direction perpendicular to its axis of revolution and $Q^2P^{-2}\Omega^2 < (A - B)AB^{-1}P^{-1}U^2$. However, it requires less angular velocity to stabilize a flat top in the sidewise than elongated ellipsoid in an axial symmetrical motion.

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Gravity Measurements in the Northeastern Pacific Ocean*

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Abstract—Gravity measurements were made at sea on seven submarine cruises by the University of California Institute of Geophysics using the multiple pendulum instrument of Vening Meinesz. Stations were located to enable study of a seamount, fracture zones, and the transition region between continental and oceanic structure. The free air, Bouguer, and isostatic anomalies are given in a table of results.

Introduction—Since early 1954 the Institute of Geophysics of the University of California has been pursuing, under ONR sponsorship, a program of gravity measurements at sea, primarily in the northeastern portion of the Pacific Ocean. From its inception the program has been oriented toward the study of particular problems in the geophysics of the ocean. The areas which were deemed most interesting were the major fracture zones, seamounts, deeps, and the transition zone between continental and oceanic structure. Significant numbers of stations associated with most of these topics have now been made at locations, and using methods, which will be described below.

Instrumentation—The basic instrument used for all these measurements was the three pendulum apparatus of *Vening Meinesz* [1929] loaned to the Institute for a two-year period. The equipment included the long-period pendulums [*Vening Meinesz*, 1941] to provide the necessary information for making the correction terms developed by *Browne* [1937]. The only alterations from the instrumentation used by Vening Meinesz were those associated with the timing system and the measurement of the depth of the submarine.

Following *Ewing* [1937], and *Browne* and *Cooper* [1950], a quartz crystal controlled oscillator was used to provide the time standard. The oscillator itself was a 100 kc, GT cut quartz instrument of the type used in master Loran stations [*U.S. Bureau of Ships*, 1946] and was lent by the U.S. Coast Guard. A frequency divider designed and constructed by the Naval Research Laboratory [*Bey* and *Hastings*, 1953] converted the 100 kc output to a one-kc signal which was used to drive the timing-marker motor. Performance of the timing system was compared with standard signals broadcast by WWV. Variations of frequency of 1 part in 10^7 or less were commonly observed with maximum discrepancies not exceeding 3 in 10^7 at any time.

The submarine's depth was measured by a Statham strain gage pressure sensing element and Speedomax recorder in an arrangement suggested by F. E. Snodgrass of Scripps Institution of Oceanography. With this instrumentation, absolute pressure can be measured with sufficient accuracy to allow determination of submarine depth to within ± 10 cm. The Speedomax record also yields the value of the vertical velocity at the beginning and end of each observation. The uncertainty in the velocity information is less than 1 cm/sec.

The entire instrument system was first assembled and tested at the University of California Institute of Geophysics in the spring of 1954 and this location was subsequently used as the base station for all the measurements. The first sea trials were made immediately thereafter on board USS *Baya* in March–April 1954 with the cooperation of the Navy Electronics Laboratory which had operational control of *Baya* for that period. During this portion of the operation we were fortunate in having B. C. Browne of Cambridge University present to render advice and assistance in adjusting the equipment and establishing operating routines.

Operations—Working within the scope of authority given by the Chief of Naval Operations through the Chief of Naval Research, direct arrangements were made with Commander Submarines Pacific Fleet and Commander Submarine Flotilla ONE in San Diego for seven cruises on board various submarines. Three were made on USS *Baya* in April 1954, June 1954, and October 1955, two were on USS *Rasher* in July and September 1954, and two on USS *Raton* in October and December 1954.

The first *Baya* cruise was devoted to initial tests off San Diego at stations 1 and 2, and to estab-

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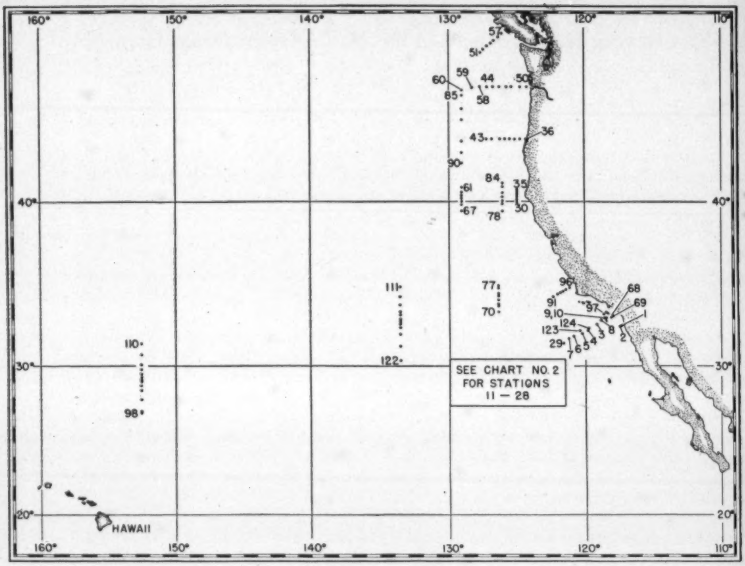

FIG. 1 – Positions of gravity stations

lishing a profile across the continental borderland. To this end stations 3 through 10 (Fig. 1) were made, passing across the northern tip of San Clemente Island and out to sea in a generally southwesterly direction. Navigation on this cruise was good inasmuch as runs between stations in the vicinity of San Clemente were of short duration and over regions in which the bathymetry is well known and of sufficient relief to provide a good auxiliary reference system.

The focal point for the second *Baya* cruise was Jasper Seamount, a prominent bottom feature located near 30°30′N and 122°40′W (Fig. 1). This peak, rises from a sea-floor depth of about 2300 fathoms to a peak only about 300 fathoms below the surface. Stations 11 through 29 were disposed about the top of the seamount as shown in Figure 2. Navigation was done relative to a marker buoy anchored, at the beginning of the operation, at a point on the summit of the mount. The topography of the seamount was determined by superposition of the sounding records made along the tracks from station to station, and previous sounding tracks made by expeditions from the Scripps Institution of Oceanography and the Navy Electronics Laboratory.

The first *Rasher* cruise marked the beginning of a series of runs between San Diego, California, and Seattle, Washington. In all of these cruises, observations were made in the Geology Building of the University of Washington with the assistance of Frank Neumann in order to check the performance of the pendulum equipment.

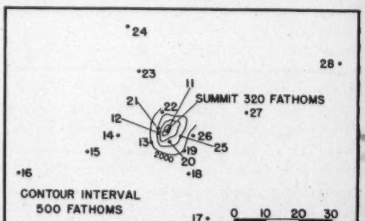

FIG. 2 – Gravity survey stations in the vicinity of Jasper seamount

TABLE 1 – *Gravity results*

Station	Latitude N	Longitude W	Corrected sounding	Anomalies				Note
				Free air	Bouguer	Airy T = 30 km	Hayford H = 113.7 km	
	° ′	° ′	fathom	mgal	mgal	mgal	mgal	
San Diego	32 42.1	117 14.1	—	−4	−4	−13	−19	A
1	32 35.8	117 23.4	83	0	+13	−18	−18	A
2	32 34.3	117 28.5	674	−59	+20	−21	−22	A
3	32 44.2	119 11.4	58	+45	+56	−19	−26	A
4	32 23.7	119 52.7	504	+16	+93	−42	−48	A
5	32 16.3	120 24.8	2072	−30	+229	+5	+32	A
6	31 56.2	120 48.0	2270	−18	+260	+5	+33	A
7	31 41.5	121 11.0	2070	−13	+253	−5	+13	B
8	32 56.0	118 54.2	880	−41	+69	−8	−9	A
9	33 03.6	118 37.2	49	+32	+43	−16	−13	A
10	33 04.1	118 33.1	630	−55	+19	−39	−39	A
11	30 31.6	122 42.1	364	+94	+216	−39	−40	B
12	30 31.0	122 46.6	1529	+22	+240	−21	−21	B
13	30 28.0	122 48.4	2018	−7	+245	−17	−16	B
14	30 29.8	122 59.1	2352	−28	+260	−15	−7	B
15	30 24.6	123 09.7	2348	−24	+265	−12	−4	B
16	30 17.8	123 33.7	2450	−34	+262	−22	−11	B
17a	30 03.1	122 26.6	2349	−31	+259	−21	−9	B
17b	30 04.7	122 27.6	2341	−32	+259	−22	−11	B
18	30 18.6	122 34.0	2177	−19	+250	−22	−14	B
19	30 25.6	122 36.1	2141	−16	+242	−20	−19	B
20	30 28.0	122 41.0	1136	+45	+230	−26	−28	B
21	30 32.2	122 44.1	1181	+44	+230	−30	−29	B
22	30 37.0	122 42.6	2036	−13	+237	−24	−23	B
23	30 49.2	122 52.0	2300	−27	+259	−16	−6	B
24	31 02.7	122 56.0	2385	−31	+257	−17	−6	B
25	30 28.8	122 37.1	1500	+19	+236	−21	−21	B
26	30 30.0	122 32.6	2040	−10	+242	−18	−16	B
27	30 37.2	122 14.1	2267	−32	+249	−22	−11	B
28	30 50.5	121 46.4	2319	−39	+246	−24	−11	B
29	31 24.5	121 36.2	2103	−24	+249	−17	0	B
30	39 58.2	124 56.2	892	−28	+89	−38	−38	B
31	40 08.5	124 59.1	610	−5	+78	−38	−41	B
32	40 16.4	124 57.0	493	+9	+78	−32	−35	B
33	40 25.4	124 57.7	1321	−67	+89	−29	−29	B
34	40 37.8	125 00.0	1486	−61	+119	−15	−5	B
35	40 46.6	124 58.9	1502	−55	+128	−3	+8	B
36	43 34.7	124 23.0	64	0	+8	−12	−25	B
37	43 33.4	124 45.0	288	−56	−18	−70	−77	B
38	43 34.4	125 07.3	794	−30	+68	−21	−21	B
39	43 35.2	125 32.7	1732	−60	+149	−12	+12	B
40a	43 35.5	125 52.7	1712	−16	+194	+14	+39	B
40b	43 34.1	125 48.9	1692	−26	+183	+4	+29	B
41	43 35.5	126 12.4	1706	−8	+204	+14	+39	B
42	43 35.5	126 41.9	1655	−10	+197	+4	+21	B
43	43 38.9	127 09.2	1650	−10	+197	+1	+15	B
44	46 13.7	127 06.3	1547	0	+194	+14	+32	B
45	46 14.5	126 41.2	1542	−5	+187	+15	+31	B
46	46 15.2	126 13.8	1481	−12	+173	+11	+28	B
47	46 15.1	125 43.5	1423	−27	+146	+7	+23	B
48	46 13.9	125 17.5	852	−18	+93	−11	−2	B
49	46 16.8	124 46.3	397	−31	+22	−36	−36	B
50	46 18.4	124 17.5	44	−40	−34	−57	−62	B
51	47 58.0	127 38.7	1512	−4	+185	+18	+38	B
52	48 07.6	127 24.5	1492	−5	+181	+21	+43	B
53	48 16.8	127 08.1	1465	−24	+159	0	+24	B
54	48 28.0	126 57.6	1434	−38	+135	+6	+25	B
55	48 41.1	126 40.9	735	−26	+66	−19	−13	B

TABLE–1 *Continued*

Station	Latitude N	Longitude W	Corrected sounding	Anomalies				Note
				Free air	Bouguer	Airy T = 30 km	Hayford H = 113.7 km	
	° ′	° ′	fathom	mgal	mgal	mgal	mgal	
56	48 48.3	126 21.8	101	+9	+23	−21	−23	B
57	48 55.5	126 02.2	40	−30	−23	−54	−55	B
58	46 15.0	127 44.0	1568	−3	+193	+8	+22	B
59	46 11.7	128 13.1	1566	−2	+196	+10	+22	B
60	46 10.4	128 53.9	1505	−2	+189	+8	+14	B
61	40 45.7	128 57.2	1821	+13	+243	+13	+16	B
62	40 34.7	128 57.2	1815	+19	+249	+14	+14	B
63	40 26.0	129 02.7	1815	+4	+237	−4	−3	B
64	40 12.7	129 01.3	2536	−79	+213	−59	−43	B
65	40 01.8	129 04.5	2591	−63	+242	−51	−25	B
66	39 49.2	128 58.2	2591	−45	+274	−26	−1	B
67	39 31.6	128 58.8	2452	−17	+294	−9	+12	B
68	33 08.5	118 16.9	638	−41	+37	−10	−14	A
69	33 16.1	118 01.6	450	−19	+37	+3	−2	A
70	33 25.7	126 20.6	2416	−15	+291	−12	−1	B
71	33 45.7	126 25.2	2528	−26	+288	−20	−7	B
72	33 57.6	126 19.4	2579	−25	+293	−18	−4	B
73	34 12.1	126 19.2	2568	−18	+304	−10	+6	B
74	34 25.6	126 20.1	2573	−17	+307	−11	+7	B
75	34 39.3	126 21.9	2619	−20	+308	−12	+6	B
76	34 53.1	126 24.5	2619	−25	+304	−18	+1	B
77	35 06.0	126 23.1	2635	−27	+303	−17	0	B
78a	39 35.4	126 01.6	2142	−17	+252	+1	+28	B
78b	39 33.5	125 56.4	2140	−12	+256	+6	+32	B
79	39 52.3	125 57.2	2023	−26	+230	−11	−14	B
80	40 06.0	125 57.1	2096	−59	+197	−39	−8	B
81a	40 19.0	125 57.5	1505	−35	+164	−44	−29	BS
81b	40 16.9	126 02.1	1763	−40	+182	−32	−15	B
82	40 33.5	126 08.2	1704	−5	+210	+5	+22	B
83	40 50.0	126 02.5	1727	−8	+209	+7	+25	B
84	41 04.5	126 00.3	1727	−10	+207	+5	+26	B
85	45 45.9	128 56.6	1537	−1	+192	+9	+14	B
86	45 10.1	128 59.2	1551	−3	+191	+3	+9	B
87	44 36.8	128 56.5	1535	−5	+187	−3	0	B
88	43 20.9	128 59.5	1784	−12	+212	−4	+8	B
89	42 48.1	128 59.7	1836	−4	+225	+3	+12	B
90	42 12.7	128 58.1	1836	−9	+221	−2	+6	B
99	34 25.3	122 24.6	2318	−22	+265	+4	+37	B
92	34 30.6	122 08.5	2218	−31	+246	0	+34	B
93	34 35.1	121 53.4	2067	−52	+206	−7	+23	B
94	34 38.2	121 42.0	1607	−49	+144	−25	−13	B
95	34 46.1	121 22.2	308	−5	+39	−56	−67	B
96	34 54.7	121 04.4	296	−13	+25	−30	−47	B
97	33 20.9	118 44.6	747	−69	+20	−34	−37	A
98	26 58	152 35	3027	−12	+358	−8	−2	BL
99	27 02	152 31	2959	−3	+366	−1	+6	B
100	27 47	152 25	2923	+5	+375	+6	+14	BL
101	28 26	152 28	3010	+2	+373	+4	+12	B
102	28 45	152 28.5	2935	+6	+373	+7	+13	B
103	29 00	152 28.5	2960	+6	+373	+9	+15	B
104	29 10	152 28	2810	−8	+343	−14	−13	B
105	29 21	152 28.5	3120	−15	+362	−4	+4	B
106	29 31	152 27	2950	−10	+360	−8	0	B
107	29 45	152 28.5	2905	−12	+353	−11	−6	B
108	30 07	152 24	2830	+23	+374	+24	+23	B
109	30 45	152 27	2860	+7	+365	+9	+12	B
110	31 31	152 29.5	2790	+16	+367	+12	+13	B
111	35 00	133 29.3	2850	−12	+347	−7	+10	C

TABLE 1 – *Concluded*

Station	Latitude N	Longitude W	Corrected sounding	Anomalies				Note
				Free air	Bouguer	Airy T = 30 km	Hayford H = 113.7 km	
	° ′	° ′	fathom	mgal	mgal	mgal	mgal	
112	34 23	133 28.5	2830	−20	+329	−17	−3	C
113	33 52	133 29.0	2725	−21	+320	−17	−6	C
114	33 28	133 27.7	2690	−18	+314	−14	−7	C
115	33 16	133 25	2625	−26	+301	−22	−16	C
116	33 00	133 27.5	2455	−32	+287	−35	−33	C
117	32 52	133 28	2265	−5	+301	−15	−12	C
118	32 40	133 31	2530	−11	+312	−8	−2	C
119	32 27	133 27.5	2600	−34	+291	−33	−25	C
120	32 03	133 27	2520	−23	+303	−20	−13	C
121	31 21	133 34.5	2610	−5	+319	+7	+7	C
122	30 18	133 34.5	2370	−4	+291	−9	−11	C
123	32 16	120 24.0	2095	−35	+226	+1	+29	C
124	32 25	119 48.0	637	−7	+84	−51	−57	C

Notes: A Rms error of free air anomaly = 2.5 mgal.
B Rms error of free air anomaly = 3.8 mgal.
C Rms error of free air anomaly = 4.5 mgal.
L No pendulum observation. Gravity value from LaCoste-Romberg gravity meter.
S Sounding unreliable because fathometer broke down just before start of measurement. Sounding given is estimated from last recorded soundings and bathymetric charts.

The *Rasher*'s northward run provided the first opportunity to accumulate data on the major fracture zones which extend into the Pacific from the west coast of North America. Stations 30 through 35 constitute a profile across the Gorda Escarpment at the continental end of the Mendocino Escarpment. In addition, two profiles (stations 36–43, and 44–50) were made across the continental shelf out from the Oregon coast, one at latitude 43°35′N and one at 46°15′N, opposite the mouth of the Columbia River. On the return trip, two months later, a profile was made across the continental borderland off Vancouver Island (stations 51–57), and three more stations were added (58, 59, 60) to the Columbia River mouth profile. Following this, seven stations (61–67) were located to provide a profile across the Mendocino Escarpment at longitude 129°00′W.

The two cruises on board USS *Raton* followed much the same pattern as the preceding two with USS *Rasher*. On the northward trip two stations (68 and 69) were added to the shoreward end of the continental borderland profile started with stations 3 through 10 This was followed by an eight station (70–77) profile across the Murray Fracture zone at longitude 126°20′W, and a profile across the Mendocino Escarpment at longitude 126°00′W (stations 78–84). Returning southward in December six stations (85–90) were added on longitude 120°00′W extending that profile across the Mendocino Escarpment to a total length of about 375 miles. A profile across the continental borderland off Point Conception was then made (stations 91–96) and the cruise completed by the addition of station 97 off Santa Catalina Island.

In October 1955 it became possible to use USS *Baya* on a trip from Hawaii to San Diego. The opportunity was taken to make two profiles across the Murray Fracture zone as well as to operate the pendulum equipment and the recently developed LaCoste-Romberg submarine gravity meter simultaneously. Results of this comparison will be reported separately. In order to carry out this operation, two of us (FNS and GLB) traveled by MATS aircraft with the equipment to Oahu, T. H. The instrument was assembled and a check station was made in the Bishop Museum in Honolulu at a location established by Woollard. Following successful completion of this test the pendulums were installed in the *Baya* at the U. S. Submarine Base at Pearl Harbor, T. H., and a station was made alongside the sea wall at berth Sail 13. The next 25 stations completed during the cruise were divided into two groups, each constituting a north-south line across the fracture zone, one at longitude 152°30′W and the other at 133°30′W. The last two stations on this trip (123 and 124) were made at the seaward end of the San Clemente Island profile near stations 4 and 5.

The latitudes and longitudes of the stations,

together with the observed soundings and free air, Bouguer, and isotatic gravity anomalies are shown in Table 1. The soundings have been corrected according to the British Admiralty *Tables of the velocity of sound in pure water and sea water* (1st ed.), the Bouguer anomalies are computed for a density of 2.67 gm/cc, and the isostatic anomalies are computed for the Airy-Heiskanen hypothesis for local compensation and a 30 km crust, and for Hayford's hypothesis with H = 113.7 km. E. Stiel assisted greatly in the computational work of reducing the pendulum records and of making the topographic and isostatic corrections.

In summary, five continental borderland profiles involving 42 stations and one study of a seamount comprising 19 stations have been made. Sixty additional stations are distributed on six profiles across fracture zones, three across the Murray fracture zone and three across the Mendocino escarpment. Interpretation of these results will be discussed in future papers dealing with the individual geophysical problems.

Acknowledgments—This work represents one of the results of research carried out under contract Nonr 233 (19) with the Office of Naval Research. It would not have been possible without the cooperation and support of many organizations and individuals. In particular, thanks are due to F. A. Vening Meinesz for making his pendulum equipment available to us for this prolonged period. B. C. Browne's assistance at the start of the project was invaluable and the support of University of Washington as given by Frank Neumann contributed significantly to our ability to carry out our operations satisfactorily.

G. P. Woollard and J. C. Rose provided us with base-station information and tied in the UCLA and San Diego stations with the world-wide gravity net. J. L. Worzel also was kind enough to provide advice and information as to the locations of stations previously made in the San Diego area and the North Pacific by Lamont Geological Observatory.

Work of this sort cannot proceed satisfactorily without the wholehearted cooperation of the submarine operating personnel. In every case this was abundantly supplied. Our thanks, therefore, go to the commanding officers: C. B. Bishop and E. M. Masica of the *Baya*, R. W. Stecher of the *Rasher* and J. K. Wills of the *Raton*.

This work has been closely correlated with other major geophysical investigations in progress in the Pacific. We are indebted to R. R. Revelle, R. W. Raitt, and H. W. Menard for their assistance and advice in planning the various cruises. Throughout we have had the firm support of L. B. Slichter, director of the University of California Institute of Geophysics.

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The Columbus Geoid

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Abstract—The author gives a summary of the preparatory work, collection of the needed gravity material, reduction method used, the gravity anomaly maps of different types needed, and the details of the method of computation of the geoid. Using the available materials, 6679 squares of 1° × 1°, four times larger than was available in 1928, several new gravity formulas have been derived. The globe was divided into 36 longitude zones of 10°. A diagram and table give an idea of the corrections to the International Gravity Formula obtained from different zones. When all gravity observations made in the oceans are available, the equatorial value of gravity may get a small negative correction.

The geoid in Europe, where Tanni already had rather good material, will remain nearly unchanged, but the geoid in America, in the Atlantic, and in India changes materially as a result of additional gravity observations, particularly at sea. Sketches of portions of the geoid are given. The astro-geodetically computed geoid of Europe, by Bomford, is compared with the Columbus geoid.

This is the first report concerning the results of the World-Wide Gravity Project for which we have worked for more than six years in the Mapping and Charting Research Laboratory of Ohio State University. When we started this program in 1950 I promised that the essential part of the work could be done in three years. Unfortunately, and fortunately, this was not the case; unfortunately, because I could not keep my word; fortunately, because we now have much more gravity material at hand than we would have had two or three years earlier. The delay was brought about, essentially, by the fact that we had to wait nearly one and one-half years before the contract was signed, and its amount was not as high as we had suggested.

In my opinion we are not very far from the truth if we say that the most important and actual problem in geodesy at the present time is the determination of the undulations N of the geoid and deflection of the vertical components ξ and η. If and when this has been done, the serious 'dualism' between the reference ellipsoid and the geoid can be eliminated. We reduce the geodetic observations to the sea level, or geoid, but we have to carry out our geodetic computations along the reference ellipsoid. Where the difference between these surfaces has not been known, it has, in general, been neglected. Also, in the determination of the size and shape of the reference ellipsoid, the deflections of the vertical play a decisive role. When these quantities N, ξ, and η are known, then we can correct the systematic errors of the triangulation brought about by the deflection of the vertical at the observation points, as well as reduce the base lines from the geoid to the ellipsoid. The knowledge of N, ξ, and η at the initial points or at some other astro-geodetic points of different geodetic systems enables us to convert the existing geodetic systems to the same world geodetic system, even across the oceans [*Heiskanen*, 1950, 1951, 1952].

Because of these facts the main emphasis of the gravity project of the Mapping and Charting Research Laboratory has been to determine gravimetrically the important quantities N, ξ, and η, which are independent of the size of the reference ellipsoid, and of the more or less unknown deflections of the vertical at the initial points of the geodetic systems.

The physical basis of the gravimetric method (or physical geodesy) is the fact that the gravity anomalies Δg and N, ξ, and η are mainly brought about by the disturbing masses Δm. The gravity anomalies Δg can be observed; the quantities N, ξ, and η computed. These quantities are nearly absolute. The only quantity which, indirectly, enters into the gravimetric computations, is the flattening α of the reference ellipsoid. This is because α is connected with the coefficient β of the $\sin^2\varphi$ term of the gravity formula. If we change α, β will be changed also, and Δg as well. However, even the β term can be best computed gravimetrically (or astronomically).

The mathematical basis of these computations is, of course, the Stokes function (for N); and its derivatives, the Vening Meinesz functions (for ξ and η).

To get ξ and η gravimetrically it is necessary to know the gravity field in the neighborhood of the

computation point very accurately and also the general nature of the field beyond. Fortunately, the effect of the gravity fields of large zones far from the computation point is rather small and changes slowly from one point to another. In the determination of ξ and η, the effect of the gravity field beyond the boundary of 3° has, according to our experience, never been more than four seconds and beyond the boundary 20° has not exceeded two seconds. Therefore, even now, there exist quite large areas where ξ and η can be computed with considerable accuracy, provided the gravity anomalies of the immediate neighborhood are sufficiently well known.

As to the N-values, we do not need the gravity field near the computation point as accurately as for ξ and η, but it must be known to some extent even to the antipodes. There are, however, two zones of about 20°, the effects of which are very small. I mean the belts of 10° on both sides of the circle $\psi = 38°58'$ and $\psi = 117°40'$, along which the Stokes function is zero. Since the gravity field of the whole world is not yet known, we cannot determine exact N-values. On the other hand, the corrections to the obtained N-values are relatively small and for large areas, for instance for Europe, are nearly constant. Consequently, the shape of the geoid can even now be obtained with rather good accuracy. When more gravity data become available we can compute how many meters the N-values have to be increased or decreased in different parts of the world.

Our main problem was, of course, to try to gather all available gravity material of the world. It took quite a bit of time, required extensive correspondence to scientific organizations, universities, oil companies, and individual scientists, and several trips to Europe. We have had success; 35 countries have given material, in several instances even unpublished data.

The gravity observations at sea carried out by Vening Meinesz, and, during the last decade, by the Columbia University group under the leadership of the diving American, J. Lamar Worzel, have opened wide areas of the oceans to the gravimetric studies. The flying American, G. P. Woollard from University of Wisconsin and his group have connected not only all continents but also innumerable ocean islands to the same world gravimetric system. These contributions have made it possible for us to start the computations of the quantities N, ξ, and η.

The procedure has been this. (1) We have prepared catalogue cards for every gravity base station. These cards reveal the change of the base values during the decades. Of course, the most accurate base values have been used. (2) Another card catalogue gives the principal facts of the gravity stations of every square degree where data exist.

The carefully analyzed free-air anomalies have been plotted on the set of maps 5° × 5° which cover the world. From these values have been estimated the mean gravity anomalies of 1° × 1° squares as well as 5° × 5° squares; in some cases also the mean anomalies of the 10′ × 10′ squares. The free-air anomalies depend on the elevation of the ground. It must be so because isostatic compensation according to the free-air reduction occurs at sea level, in contrast to the depths of 25 to 40 km of the real compensating layers. The fact that free-air anomalies have a pronounced elevation term is one evidence of the isostatic equilibrium.

To compute the elevation correction *Uotila* [1957] has plotted the gravity anomalies of every square degree of rugged topography as a function of the elevation. The mean elevation of the square in question was then estimated from the topographic map. The mean gravity anomaly corresponding to the mean elevation of the square is taken from the appropriate graph.

The layout of corrected mean free air anomalies of the 1° × 1° squares was recorded on a series of International Hydrographic Bureau bathymetric maps. These basic maps were then also used for the interpolation and extrapolation of the gravity anomalies of the unsurveyed areas. The layout of corrected mean free-air anomalies was also prepared in stereographic projection because this type of projection is best for our purpose. The ψ-curves of equal distance from the computation point, as well as the curves of equal azimuth, are circles in stereographic projection, and consequently easy to draft. From these 1° × 1° maps similar maps were made for the mean gravity anomalies of the 5° × 5° squares.

A very important problem is the filling of the gaps in the gravity anomaly field. *Hirvonen* [1953, 1956], continuing the studies of *de Graaff Hunter* [1935], has studied this problem for a couple of years on the basis of the extensive material our Laboratory had available. I will only briefly mention his main conclusion. One gravity observation cannot represent an area larger than 3° × 3°. Further, for unsurveyed areas larger than 3° × 3°,

the gravity anomaly zero represents the mean gravity anomaly more closely than the extrapolated anomaly. So we have adhered to this concept throughout our work.

We have been tempted on occasion to develop the gravity anomalies in spherical harmonics but have realized that this method is not yet practical. The gravity anomaly field changes so fast from point to point that we would need spherical harmonics at least to the 50th order to obtain reliable representation of the real gravity field. The geoid of *Zhongolovich* [1952] is an example of this. On the basis of poor gravity data he developed gravity anomalies all over the world in spherical harmonics and has obtained undulations of the geoid, on the average 2.5 times larger than the gravity observations permit. Consequently, a geoid with zero undulations, that is the ellipsoid itself, is a better representative of the real geoid than the geoid of Zhongolovich. Therefore, the Stokes function has been used instead of the development of anomalies in spherical harmonics.

Since the gravity formula plays an important role in these computations, we have computed several gravity formulas—about 40—based on our large material, altogether the mean gravity anomalies of 6679 squares 1° × 1°, dividing the gravity material in different longitude zones. One formula is computed for the northern, another for the southern hemisphere.

The best suitable gravity formulas for the whole Earth are [*Heiskanen* and *Uotila*, in press]:

Using the mean free air anomalies 1° × 1°

$$\gamma = 978.0496\ (1 + 0.0052934\ \sin^2\phi - 0.0000059\ \sin^2 2\phi);\ \text{flattening}\ \alpha = 1/297.4$$

Using the mean free air anomalies 5° × 5°

$$\gamma = 978.0497\ (1 + 0.0052902\ \sin^2\phi - 0.0000059\ \sin^2 2\phi);\ \text{flattening}\ \alpha = 1/297.2$$

For the convenience of the readers we enclose here also the International Gravity Formula

$$\gamma = 978.049\ (1 + 0.0052884\ \sin^2\phi - 0.0000059\ \sin^2 2\phi);\ \text{flattening}\ \alpha = 1/297.0$$

The author is particularly glad that the equatorial value of gravity of these formulas differ rather little from the equatorial value of the International Gravity Formula [*Heiskanen*, 1928]. Both the mean gravity anomalies of the squares 1° × 1° and 5° × 5° give very close to the same result, the difference being only 0.1 mgal. Also, the corrections to the quantity β and correspondingly to the flattening value α are small; respectively, 1/297.4 and 1/297.2 instead of 1/297.0. So we are quite safe in using the International Gravity Formula in the geodetic studies. When all observations carried out at the oceans are available, the equatorial gravity value may get a small negative correction.

The geoid undulations N have been computed at the corners of 5° × 5° squares. Since we used the IBM machine 650 it was easier to compute than to omit the N-values for such corner points in the neighborhood of which not sufficient gravity data exist. In this computation the mean anomalies of 5° × 5° were used. Since these values are only approximate because of the great effect of the immediate neighborhood, we have computed the effect of rectangles 20° × 30° using the mean anomalies of 1° × 1°. To be able to combine both computations, the effect of the world beyond the area 20° × 30° was computed separately. We have to add to this effect only the effect of the immediate neighborhood, computed from the 1° × 1° squares, to get a better approximation for the N-values. The effect of 20° × 30° rectangles was computed at the interval of 5° along the used parallel circles. Consequently, the arc profiles are rather reliable.

On the geoid maps, Figures 1 and 2, the five-meter contour curves of the undulations N have been drafted. So far we have about 1800 N-values. Not all of them, however, can be used because of the scarcity of the gravity material in the neighborhood of the computation point. The detailed geoid of Europe is to be seen in Figures 3 and 4, in which the contour curves of undulations N at the interval of two meters are given. These maps have been drafted on the basis of 1116 N-values computed at the corners of 1° × 1° squares. Both maps give the geoid between longitudes −5° and +30°, the former for latitudes 60° to 45°; the latter for latitudes 45° to 30°.

This geoid is interesting in many respects. First, it shows that the geoid rises from +10 meters from the Baltic Sea to +45 meters in western basin of the Mediterranean. Most interesting, however, seems to be the area from Italy along the Mediterranean, over Greece to the Holy Land. In this area the gradient of the N-values is very large; in some cases even 12 meters per 10 km. Geophysical study of Europe on basis of the geoid map will be very interesting.

When *Tanni* [1948] computed the geoid at the Isostatic Institute, gravity material was quite scarce, particularly over the oceans. Therefore, it

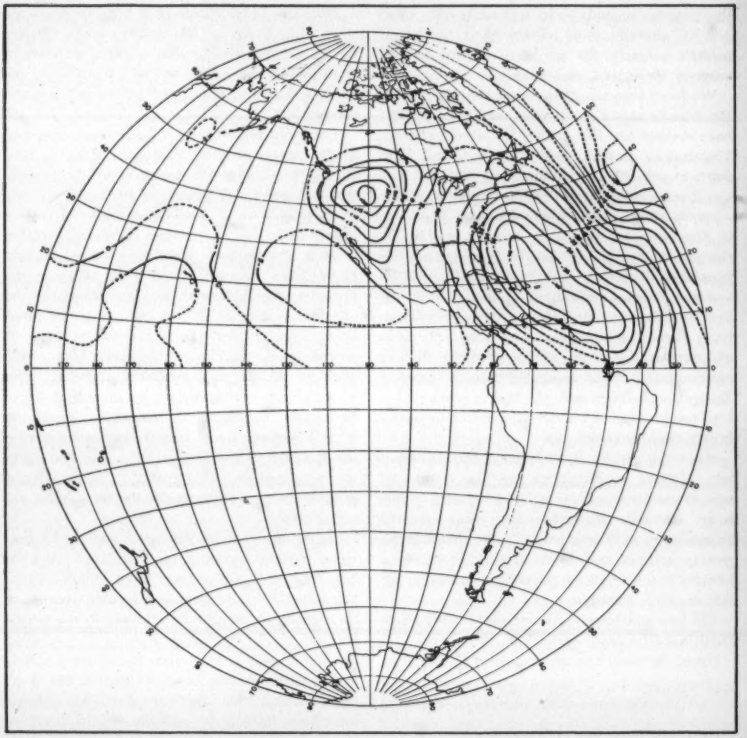

FIG. 1 – Gravimetrically computed geoid for northern portion of the western hemisphere; contour interval, five meters

is no wonder that the Columbus geoid, which also is only a tentative one, will give essentially different N-values from Tanni's geoid. As to North America, on the east coast the geoid is below the ellipsoid, rises continuously and, of course, has the highest positive values around the Rocky Mountains. Closer to the west coast the accuracy of the N-values is rather poor because only a tiny part of the southern Pacific Ocean has been surveyed gravimetrically so far.

In Europe the geoid differs less from Tanni's because he already had quite extensive gravity material from the eastern hemisphere.

The geoid of India is drastically changed. The negative N-values up to -65 m, obtained by Tanni have been reduced to -30 m. This interesting change is brought about by two factors. First, the additional observations carried out in India have shown that the mean gravity anomalies of Tanni were negatively too large, and in the highlands of Asia his positive anomalies were too small. Second, the positive gravity field at the Atlantic and in the East Indies also uplifts the geoid in India.

In the southern hemisphere gravity material is still so inadequate that the N-values have not been

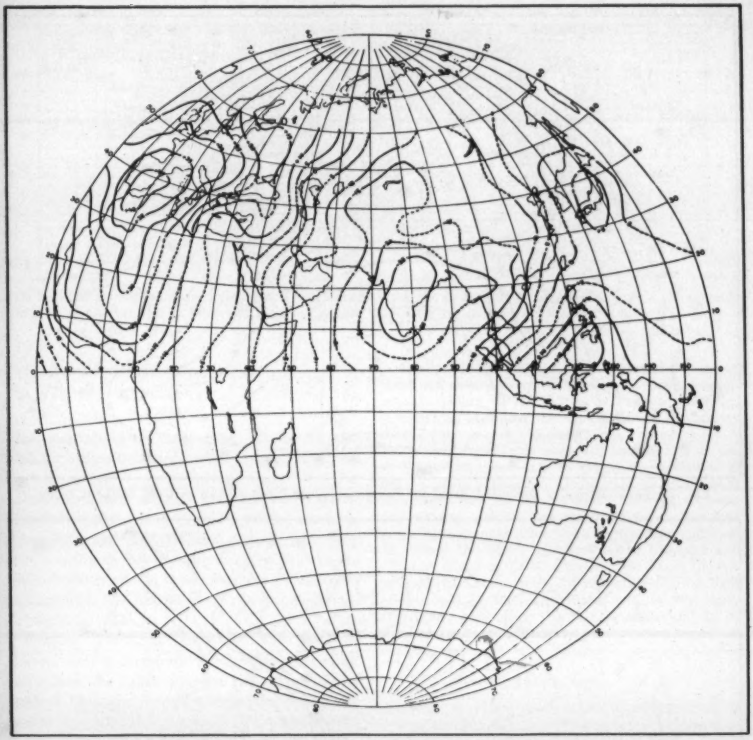

FIG. 2 – Gravimetrically computed geoid for northern portion of the eastern hemisphere; contour interval, five meters

computed there except along the latitudes $-5°$ and $-10°$. When all gravity observations at sea carried out by the Columbia University group are available, it will be possible to compute more N-values for the southern hemisphere.

The problem of the triaxiality of the Earth is interesting but is hardly any longer of importance because we now know the shape of the geoid itself. If the triaxiality exists, the gravity anomalies of the different squares could be represented by a double sine curve, so that the longitude difference between the gravity high and gravity low ought to be 90°. Also the longitude of the gravity high and gravity low ought to be approximately the same along all parallel circles. Such was the case, in fact, three decades ago when gravity observations were made chiefly in North America, Europe, and India. It so happened that in North America the gravity anomalies are systematically negative; in Europe, approximately 90°E of North America, they were strongly positive; and again in India, about 90°E, they were strongly negative. This brought several scientists, the author [*Heiskanen*, 1928] included, to the conclusion that the triaxiality was proved. Now, however, when we have many times more observations, including the

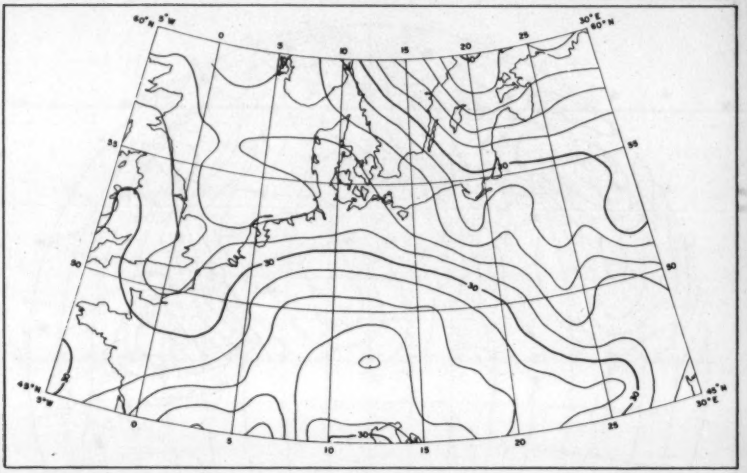

FIG. 3 – Gravimetrically computed geoid for Europe; contour interval, two meters; northern sector

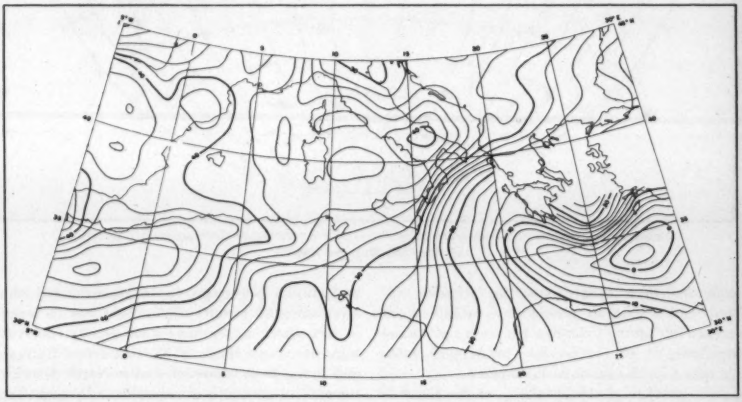

FIG. 4 – Gravimetrically computed geoid for Europe; contour interval, two meters; southern sector

invaluable gravity observations at sea, the picture seems no longer to be so simple. Figure 5 giving the distribution of the positive (+) and negative (−) gravity anomaly fields, shows that the belts of positive and negative gravity anomalies are not in meridian direction but tilted about 45°. Furthermore, the longitude difference between them varies essentially.

Uotila, in an unpublished paper, has computed the gravity formula with the longitude term. His results are the following: For the whole world

$$\gamma = 978.0516\,[1 + 0.0052910 \sin^2\phi - 0.0000059 \sin^2 2\phi + 0.0000106 \cos^3\phi \cos 2\,(\lambda + 6°)]$$

For the northern hemisphere

$$\gamma = 978.0505\,[1 + 0.0052925 \sin^2\phi - 0.0000059 \sin^2 2\phi + 0.0000131 \cos^3\phi \cos 2\,(\lambda + 10°)]$$

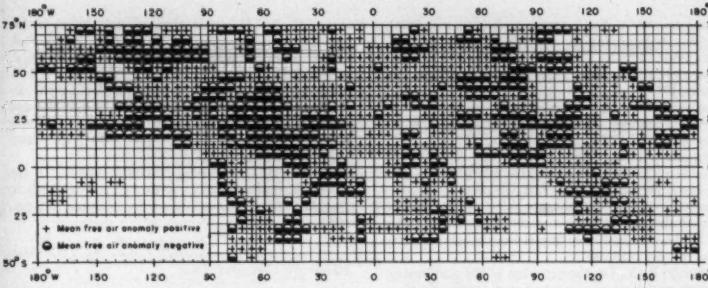

FIG. 5 – Schematic gravity anomaly map of the distribution of the mean gravity anomalies of 5° × 5° squares; note that the belts of positive and negative gravity anomalies are large, their longitude difference (from gravity high to gravity low) vary from 40° to 70°, and they are tilted about 45° from the meridian

For the southern hemisphere

$$\gamma = 978.0547\,[1 + 0.0053038 \sin^2\phi - 0.0000059 \sin^2 2\phi + 0.0000047 \cos^2\phi \cos 2\,(\lambda - 56°)]$$

The longitude of the long axis, −6°, agrees well with the values obtained earlier, but the longitude term of our gravity formula is less than half of the values obtained earlier. The longitude terms $0.0000131 \cos^2\phi \cos 2\,(\lambda + 10)$ of the northern hemisphere, and $0.0000047 \cos^2\phi \cos 2\,(\lambda - 56°)$ of the southern hemisphere disagree drastically, while the long axis is, in the southern hemisphere, at longitude +56° but in the northern hemisphere at longitude −10°.

Bomford [1954] has computed the geoid in Europe astro-geodetically. His geoid is interesting and reveals the possibilities and limitations of this method. Since the N-values of the Bomford geoid and of the gravimetric geoid differ considerably, it has created confusion in the geodetic world. However, this discrepancy is easy to explain. Bomford has not properly considered the N, ξ, and η values at the initial point Potsdam of the European datum. When we use the values N, ξ, and η obtained gravimetrically, the agreement between these two geoids is rather close. The uncorrected N-values of Bomford differ from our N-values by as much as 60 m, in contrast to the differences between the corrected Bomford values and our values which are on the average five times smaller. For instance, along the parallel 50°N the maximum value of the former difference is 55 m but in the latter case only 12 m.

In conclusion I emphasize that we can hardly get best dimensions of the Earth ellipsoid, and still less the real form of the geoid, if we neglect the important gravimetric evidence which is already available.

Acknowledgment—It is a great pleasure for me to thank the many governmental and university organizations, leading oil companies, as well as individual scientists, in particular the consultants of the gravity project from the United States and abroad, who together have made this program possible. It is my special privilege and duty to extend my gratitude to the Geophysics Research Directorate of the United States Air Force for the continuous interest, support, and patience which it has shown us during the past years. Also, I am grateful to G. H. Harding and Paul M. Pepper, the former directors of the Mapping and Charting Research Laboratory of Ohio State University, the birthplace of the Columbus geoid, for their invaluable help and cooperation; and to my many co-workers, particularly R. A. Hirvonen and U. A. Uotila, who have contributed most to the benefit of our program.

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Theoretical Investigations of the Four-Electrode Crevasse Detector

H. Norman Abramson

Abstract—Analyses based on general electromagnetic field equations were undertaken, but these proved tractable only for rather simple cases not extending to the presence of a cavity. After a study indicated magnetic induction effects to be negligible, analysis of the electrostatic field led to an expression for the potential at any point in a field, with allowance for the presence of a spherical or cylindrical cavity. A numerical solution of the Laplace equation afforded another technique, using the Southwell relaxation method. A third approach was to model the problem in a plane using conducting paper to obtain an analog solution. The analog technique was found to be the most expeditious one, and it is flexible as to the shape of the cavity cross-section. Specimen curves and tables given in the paper are expected to be useful in further studies.

Introduction—In 1955 the Southwest Research Institute, operating under contract with the Engineer Research and Development Laboratories, demonstrated and tested an experimental model of a low-frequency four-electrode crevasse detector [*Cook*, 1956]. Although the equipment was successful in locating crevasses, the various design parameters had been established empirically, and it was not considered that they represented optimal values. It seemed desirable to evaluate the device theoretically in order to determine its capabilities and limitations, with a view to advancing the design toward a system that would yield information on crevasse width, depth, and shape, on bridge thickness, and so forth. To this end a program has been proposed which would incorporate theoretical studies, model studies, and data analysis leading to a final design configuration. The present study developed along several related directions involving strictly analytical investigations, numerical analyses, and analog studies.

Consider the four-electrode arrangement of Figure 1. A low-frequency, sinusoidal current is introduced at the ice surface through the two source electrodes I_1 and I_2, establishing in the ice a displacement current with a certain flow pattern. The two electrodes e_1 and e_2 measure the potential gradient at some distance from the source electrodes. In the presence of a crevasse, this reading shows an anomaly. The device is similar in principle to equipment used in resistivity surveys.

Anaysis based on field equations—The general electromagnetic field equations were studied in an attempt at a rigorous mathematical theory to account for the field test results. The analysis assumed a single electrode, inasmuch as the complete potential field can be obtained by superposition. The aim was to determine the potentials directly from the fundamental equations. This was done for the electrostatic case, and a rather long study was made for the general case, as set forth in detail elsewhere [*Abramson*, 1956]. Some consideration was also given to the possibility of solving the equation for the electric field vector and using the result to determine the potentials.

This analysis did not consider the effects of a crevasse, because of the severe mathematical difficulties which were encountered even for the case of a homogeneous half-space. The basic assumptions involved in the analysis were as follows: (a) all electrodes hemispherical; (b) conduction currents negligible; (c) the ice field considered as an infinite half-space of homogeneous, isotropic material, with the regions near the electrodes considered as singularities; (d) zero net free charge; and (e) frequencies within the range 60–1000 c/s, and distances varying up to about one km. The analysis also did not consider the effect of a finite conductor with respect to attenuation of the wave, as ice is not a perfect dielectric.

This analysis was only partly successful, in that only the electrostatic case for a region containing no cavity was solved. It nevertheless provides some information concerning the distribution of potential near an electrode, and it points out the primary difficulties of the more general problem.

Analysis for magnetic induction effects—A somewhat different analysis was also made for the condition of no crevasse: the magnetic induction effects were calculated by direct integration. This analysis was intended to clarify three basic points. First, it was thought that the effect of magnetic induction was larger than that of the electrostatic induced potential. Second, experimental measurements had shown little or no frequency dependence, a result conflicting with both earlier analyses

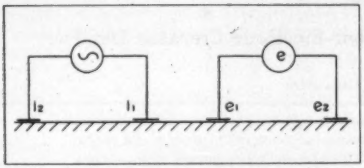

FIG. 1 – Schematic arrangement of the four-electrode crevasse detector

[*Cook*, 1956; *Abramson*, 1956]. Third, it was desired to obtain information as to the phase angle between current and potential. The analysis is presented in the report just cited, where it is compared with the electromagnetic theory and with available field data. These studies indicate that the magnetically induced effect is negligible.

Analysis based on electrostatic potential theory with cavity present—Because of the low frequency used, an analysis based on an electrostatic field seemed promising. Two alternative approaches depend on whether we consider the ice field to be a dielectric medium or a conducting medium. In the latter case, we would be interested in determining the so-called 'apparent resistivity' of the medium at different depths. This can be calculated for certain electrode configurations and crevasse shapes.

The effective current penetration will increase with separation of the source electrodes, permitting the resistivity at different depths to be determined. When a cavity is present, the plot of apparent resistivity will show an anomaly. The apparent depth at which the anomaly occurs is not in general the actual depth of the cavity; however, an applicable theory should yield a relation between apparent and true depth. It is expedient to represent the electrodes by point sources and sinks, and the cavity by an appropriate combination of point sources and sinks. Maxwell's method of electric images [*Jeans*, 1925] serves to determine the potential at a given point in the solid infinite half-space, the resistivity of the solid being assumed.

We shall consider the ice field as a dielectric medium in this problem. In the physical problem the ice field is overlain by air, which is also a dielectric medium; the analysis must consider the air as an infinite dielectric.

With point electrodes and a spherical cavity, the problem is strictly three-dimensional. With point electrodes and a cylindrical cavity of circular cross section at right angle to the line of electrodes, the result is a mixed two-dimensional and three-dimensional problem. The strictly two-dimensional problem would involve line electrodes placed parallel to the axis of the two-dimensional cavity.

Palmer [1954] solved the problem of a symmetrical electrode arrangement over a spherical cavity (see Fig. 2). His analysis, which is also valid for the cylindrical cavity with point electrodes, has been extended in the present work to the electrode arrangement of Figure 1, with the cavity located ahead of both source electrodes. This extension culminated in an expression (see Appendix, Eq. 15) for the potential at any point in a field containing a spherical or cylindrical cavity.

Numerical analysis—If the ice is again taken as a homogeneous dielectric subjected to a charge-free electrostatic field, the potential distribution is governed by the Laplace equation. It is again assumed that the overlying air is an infinite dielectric. In a two-dimensional problem, the Laplace equation may be solved for any electrode configuration and for any crevasse configuration by numerical techniques, specifically and quite conveniently, by a finite-difference technique known as the Southwell relaxation method [*Allen*, 1954]. The problem is set up in terms of a finite-difference solution, and values of the potential are obtained within the region of interest by a trial process, with attention to the appropriate boundary conditions, which were here taken to be as follows: (a) The potentials at infinity are zero, and (b) the po-

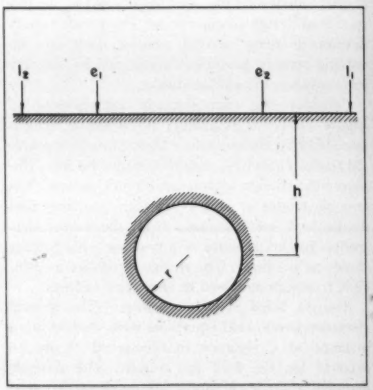

FIG. 2 – Spherical or cylindrical cavity with symmetrical electrode arrangement

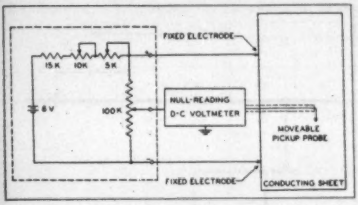

FIG. 3 – Circuit diagram for conducting sheet analogy

tential gradients normal to all free surfaces (ice surface and crevasse boundaries) are zero. The procedure is well known, and the results obtained are discussed in a later section.

Analog technique—Under the same basic assumptions, we now consider a somewhat different method of solving the two-dimensional Laplace equation. If a sheet of conducting material (paper, metal, or liquid) is subjected to a given voltage distribution, Laplace's equation represents the current flow in the conducting material. If the conducting sheet is subjected to the boundary conditions characterizing our problem, we have a solution by analogy upon measuring potentials in the conducting medium [*Soroka*, 1954]. 'Teledeltos' facsimile paper was used in the present study. Figure 3 is a typical circuit diagram, and Figure 4 shows the analog set-up. The technique affords an exact analog to the numerical procedure, but the solution is obtained much more easily. For very irregular boundaries, the computational method becomes impracticably laborious, while the analog method entails no increase in complexity.

Results of numerical examples—In order to establish the techniques of the conducting-sheet analogy, it was decided to determine the potential distribution for the case of no cavity by both the numerical computation and the analogy, and to compare these results with an analytical solution [*Jakosky*, 1950, pp. 475–478]. For all three methods, it is assumed that the potential distribution satisfies Laplace's equation. The comparison is made in Figure 5, which shows the variation in potential along the line joining the two electrodes. It may be noted that the conducting-sheet analogy gave results in good agreement with the analytical curve, while the numerical computation yielded only fair agreement. In this regard, an essential point to be noted is that the potentials calculated by the relaxation method drop down to zero very quickly as one moves away from the electrode. The computa-

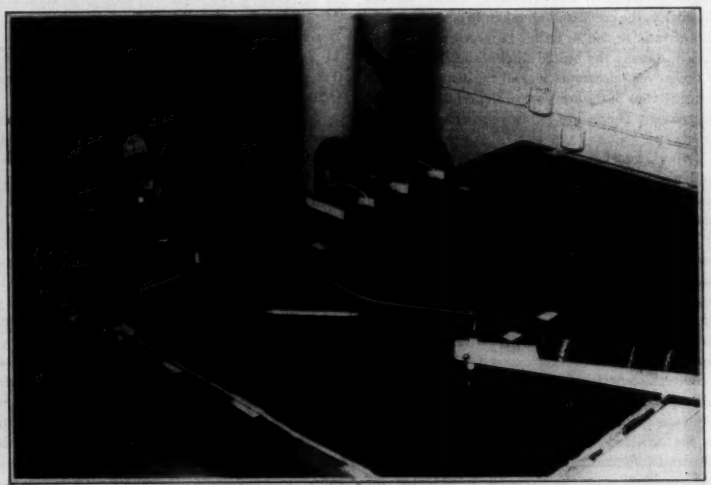

FIG. 4 – Conducting sheet analogy

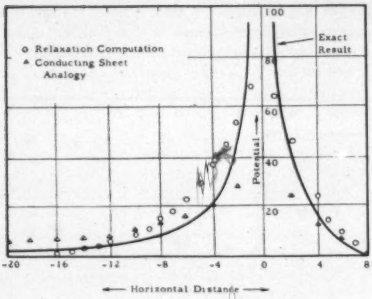

FIG. 5 – Comparison of potential distributions with no cavity present [*Slater* and *Frank* 1947]

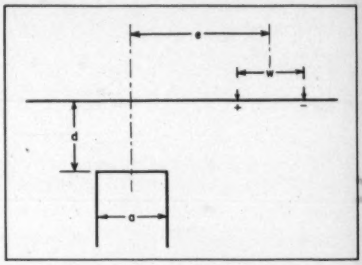

FIG. 6 – Notation for numerical examples

tion method will, however, yield any desired accuracy if the difference mesh is made sufficiently fine. In the present case a much better accuracy can be obtained simply by taking a fine mesh near the free surfaces, so as to achieve a better representation of the gradient boundary condition. Neither method will give good results close to the singularity.

The example set up for solution by both the relaxation and analog techniques is based on a single parameter, the crevasse width a. For simplicity, the crevasse was taken to be rectangular and of infinite depth. Other parameters were also varied, namely the bridge thickness d, the spacing of the current electrodes w, and the distance e from the centerline of the crevasse to the centerline of the electrodes. These are shown schematically in Figure 6.

The examples worked out by the relaxation method are described in Table 1, in terms of the parameters mentioned above. Examples worked out by the analog technique are similarly described in Table 2. The corresponding potential distributions obtained in each case are shown in Tables 3 and 4. For convenient representation, the data have been rounded off to whole numbers and presented as potential distributions in terms of distance from the crevasse centerline, the unit being the crevasse width a.

Since the configuration of the potential electrodes is completely arbitrary, the results shown in Tables 3 and 4 may be used by taking points corresponding to the selected configuration and reading the potential differences. For example, in Table 3, it may be seen that the crevasse is detected by selecting a potential electrode arrangement ahead of the plus current electrode (that is, closer to the crevasse) and taking in order examples III, II, and I.

The examples I, II, III of Table 3, obtained by the relaxation method, are directly comparable with the analog examples of Table 4 designated 0–1, 0–2, and L–2, respectively.

Table 4 is useful for examining the effects of various parameters on the potential distribution. For example, the following correlations may be studied: (a) Effect of depth only, examples L–2, L–3; (b) effect of electrode width only, J–5, M–2, N–3; (c) effect of eccentricity only, J–5, K–4, L–3; M–2, M–3; L–2, 0–1, 0–2, 0–3; (d) examples having the same crevasse configuration, J–5, K–4, L–3, M–2, M–3, N–2, N–3 for $d = a$; K–2, L–2, 0–1, 0–2, 0–3 for $d = 2a$; M–4, N–4 for $d = \frac{1}{2}a$, etc. Other correlations are, of course, possible.

It is clear that this type of data would be valuable in an optimization program. Even if model studies should not prove the validity of the underlying analysis, the data herein presented would provide important qualitative information as to the effects of variations in the parameters. This type of study, however, must be quite detailed and probably should include a larger number of parameter variations than are presented here. The shape of the crevasse may be an important one of these. Finally, field data should be correlated with any conclusions drawn from such studies.

Applications and further studies—An effective technique for studying the influence of parameter changes is the conducting-sheet analogy. Almost any electrode configuration and any crevasse shape can be so examined, conveniently and with an entirely acceptable accuracy. The technique is therefore preferable to the numerical computation (relaxation) method in almost every instance.

TABLE 1 – *Examples worked by the relaxation method*

Example	Cr. width a	Bridge th. d	El. spacing w	C. distance s
I	a	$2a$	$2a$	0
II	a	$2a$	$2a$	$2a$
III	a	$2a$	$2a$	$4a$

TABLE 2 – *Examples worked by the analog technique*

Example	Cr. width a	Bridge th. d	El. spacing w	C. distance s
J-5	a	a	2a	0
K-2	a	$\frac{1}{4}$a	2a	2a
K-4	a	a	2a	2a
L-2	a	2a	2a	4a
L-3	a	a	2a	4a
M-2	a	a	a	0
M-3	a	a	a	3a
M-4	a	$\frac{1}{4}$a	$\frac{1}{4}$a	$\frac{3}{4}$a
N-2	a	a	2a	0
N-3	a	a	4a	0
N-4	a	$\frac{1}{4}$a	2a	0
N-5	a	$\frac{1}{4}$a	a	0
N-6	a	$\frac{1}{4}$a	$\frac{3}{4}$a	0
O-1	a	2a	2a	0
O-2	a	2a	2a	2a
O-3	a	2a	2a	a

On the other hand, while the electrostatic problem can be solved by the analog method, the applicability of such solutions to the actual crevasse-detection problem is not assured. However, continuation of this program to include model studies should provide sufficient opportunity to assess the validity of the method. Note also that the method can be extended to certain classes of three-dimensional problems.

As to the electrostatic potential analysis given in the Appendix, the proposed model studies should likewise provide means to judge its applicability. If so confirmed, the results will be useful in parameter investigations directed toward attainment of optimum design of the apparatus.

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APPENDIX—ANALYSIS BASED ON ELECTROSTATIC POTENTIAL THEORY WITH CAVITY PRESENT

This analysis is an extension of the work of *Palmer* [1949] for the symmetrical electrode configuration shown in Figure 2. We assume a spherical cavity of radius r of infinite resistivity, centered at a distance h below the surface. The ice field is represented as a homogeneous isotropic material of resistivity ρ. Using the method of images, we replace (that is, represent) the cavity by a virtual current dipole with its image in the upper half-plane. (For simplicity in the analysis, we will speak of the charges constituting the dipole.) Referring to Figure 7, the center of the cavity is located at point Q and the current electrodes at

TABLE 3 – *Solutions by the relaxation method*

Distance from crevasse C.L.	No crevasse	I	II	III
−22/8a	3	4.5	0	0
−21/8a	4	5.5	0	0
−20/8a	6	6.5	0	0
−19/8a	7	7.5	0	0
−18/8a	8	8.5	0	0
−17/8a	10	10.5	0	0
−16/8a	13.5	13.5	0	0
−15/8a	18	18	0	0
−14/8a	23	23	0	0
−13/8a	29.5	29	0	0
−12/8a	36.5	36	0	0
−11/8a	43.5	44	0	0
−10/8a	53	54.5	0	0
−9/8a	68	69.5	0	0
−8/8a	...	...	1	0
−7/8a	65.5	66	2	0
−6/8a	47.5	48	3	0
−5/8a	35	35	4	0
−4/8a	25	25	5	0
−3/8a	16.5	16.5	6	0
−2/8a	9.5	9.5	7	0
−1/8a	4	4	8	0
0	0	0	12	0
1/ a	−4	−4	18	0
2/8a	−9.5	−9.5	24	0
3/8a	−16.5	−16.5	29.5	0
4/8a	−25	−25	36	0
5/8a	−35	−35	44	0
6/8a	−47.5	−48	54	0
7/8a	−65.5	−66	70	0
8/8a	...	...	...	1
9/8a	−68	−69.5	68	2
10/8a	−53	−54.5	51	3
11/8a	−43.5	−44	37	4
12/8a	−36.5	−36	25.5	5
13/8a	−29.5	−29	16.5	6
14/8a	−23	−23	9.5	7
15/8a	−18	−18	4	8
16/8a	−13.5	−13.5	−.5	12
17/8a	−10	−10.5	−4.5	18
18/8a	−8	−8.5	−10	24
19/8a	−7	−7.5	−16.5	29.5
20/8a	−6	−6.5	−26	36
21/8a	−4	−5.5	−37	44
22/8a	−3	−4.5	−51	54
23/8a	−2	−3.5	−68.5	70
24/8a	−1	−2.5	...	...

TABLE 4 — *Solutions by the analog technique*

Distance from Crevasse C.L.	No crevasse	J-5	K-2	K-4	L-2	L-3	M-2	M-3	M-4	N-2	N-3	N-4	N-5	N-6	O-1	O-2	O-3
−14/4a	0	11	2	2	0	0	5	0	1	19	31	13			8	4	6
−13/4a	1	12	3	3	0	0	5	1	1			14			9	5	7
−12/4a	1	14	3	3	1	1	6	1	1	22	37	17	0		10	5	7
−11/4a	3	16	3	3	1	1	8	1	2			18	1		12	6	8
−10/4a	6	18	4	4	1	1	8	1	2	25	46	21	4		14	6	9
−9/4a	8	21	5	5	2	2	9	1	2			23	6		16	8	10
−8/4a	13.5	25	5	5	2	2	10	1	2	31	...	27	9		19	8	11
−7/4a	23	29	7	6	4	2	11	2	2			32	13		22	9	13
−6/4a	36.5	36	7	7	4	4	14	2	4	41	41	37	17	0	30	10	14
−5/4a	53	48	8	8	5	4	16	4	4			49	21	3	41	11	17
−4/4a	...	...	9	9	5	5	21	4	5	...	26	...	28	8	...	12	20
−3/4a	47.5	41	11	11	6	6	30	4	5			43	39	14	49	14	24
−2/4a	25	24	12	13	6	8	...	5	6	27	13	26	...	27	20	15	30
−1/4a	9.5	11	13	15	8	8	19	5	6			13	28	...	10	18	42
0	0	0	16	17	9	9	0	6	8	0	0	0	0	0	0	20	...
1/4a	−9.5	−11	19	21	10	10	−20	6	8			−13	−28	...	−10	25	38
2/4a	−25	−23	23	25	11	11	...	8	9	−28	−14	−27	...	−27	−20	30	21
3/4a	−47.5	−40	31	33	12	12	−29	9	10			−45	−39	−14	−49	41	10
4/4a	...	...	...	...	14	15	−20	9	10	...	−27	...	−27	−8	...	...	1
5/4a	−53	−46	29	29	15	16	−16	10	11			−49	−21	−3	−40	38	−9
6/4a	−36.5	−34	17	18	18	18	−14	12	14	−41	−44	−37	−17	0	−29	22	−20
7/4a	−23	−28	10	4	19	20	−11	15	15			−32	−13		−22	11	−36
8/4a	−13.5	−24	4	−1	22	24	−10	19	20	−31	...	−27	−9		−19	1	...
9/4a	−8	−20	−2	−4	26	28	−9	28	29			−25	−6		−16	−8	−41
10/4a	−6	−17	−9	−9	34	34	−8	...	...	−25	−46	−21	−4		−14	−18	−28
11/4a	−3	−15	−19	−19	45	46	−8	20	20			−18	−1		−11	−35	−22
12/4a	−1	−14	...	...	...	...	−6	0	0	−22	−36	−17	0		−10	...	−18
13/4a		−11	−23	−23	41	41	−5	−20	−20			−14			−9	−39	−14
14/4a		−10	−15	−15	24	24	−5	...	...	−19	−31	−13			−8	−26	−12
15/4a		−9	−12	−11	12	12	−4	−29	−29			−10			−6	−20	−10
16/4a		−7	−9	−9	2	2	−4	−19	−19	−16	−26	−9			−5	−15	−8
17/4a		−6	−7	−7	−8	−8	−2	−12	−12			−8			−5	−11	−7
18/4a		−5	−6	−6	−20	−20	−2	−10	−10	−15	−23	−6			−4	−9	−6
19/4a			−5	−5	−38	−38	−2	−8	−8			−5			−2	−8	−4
20/4a			−4	−4	...	...	−1	−5	−5	−13	−21	−4			−2	−5	−3
21/4a			−3	−3	−41	−41	−1	−2	−2			−3			−1	−2	−2
22/4a			−3	−2	−29	−29	0	−1	−1	−12	−18	−1			0	−1	−1
23/4a			−2	−1	−21	−21		0	0			0				0	0
24/4a			−2	−1	−16	−16				−10	−16						
25/4a			−1	−1	−14	−14											
26/4a					−10	−10				−9	−13						
27/4a					−8	−9											
28/4a					−6	−6				−9	−12						
29/4a					−5	−5											
30/4a					−2	−2				−7	−10						

I_1 and I_2, with I_2 at a distance ka from the surface point over Q, which surface point is taken as the origin. We seek an expression for the potential at point P. Since the medium is not an insulator, lines of current flow will be represented by lines of an electrostatic field.

Referring to *Slater* and *Frank* [1947, p. 17], the charge at I_2 may be replaced by its image near Q, given by

$$q_2' = -\frac{rq_2}{\sqrt{(ka)^2 + h^2}} \tag{1}$$

and located at a point along I_2Q whose distance from Q is

$$\xi_2 = \frac{r^2}{\sqrt{(ka)^2 + h^2}} \tag{2}$$

Similarly we may suppose a charge near Q corresponding to I_1, and given by

$$q_1' = \frac{rq_1}{\sqrt{(k-2)^2a^2 + h^2}} \tag{3}$$

This charge is located at a distance ξ_1 from Q

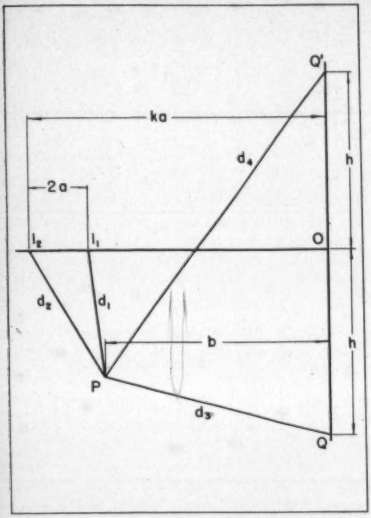

FIG. 7 – Image system for spherical cavity with unsymmetrical electrode arrangement

along I_1Q given by

$$\xi_1 = \frac{r^2}{\sqrt{(k-2)^2a^2 + h^2}} \tag{4}$$

Now with

$$q_2 = \rho I, \qquad q_1 = -\rho I \tag{5}$$

we have

$$q_2' = \frac{-\rho I r}{\sqrt{(ka)^2 + h^2}}, \quad q_1' = \frac{\rho I r}{\sqrt{(k-2)^2a^2 + h^2}} \tag{6}$$

The arrangement is as shown in Figure 8. The distance between q_1', and q_2', denoted as 2ζ, can be shown to be given by the expression

$$(2\zeta)^2 = \frac{4a^2r^2}{[(ka)^2 + h^2][(k-2)^2a^2 + h^2]} \tag{7}$$

We will assume, however, that the axis of the two charges q_1' and q_2' is horizontal as shown in Figure 9. This leads to the expression

$$m = \frac{kar^2}{(ka)^2 + h^2} \tag{8}$$

whence it is clear that $AQ \ll h$, in accordance with *Palmer* [1954].

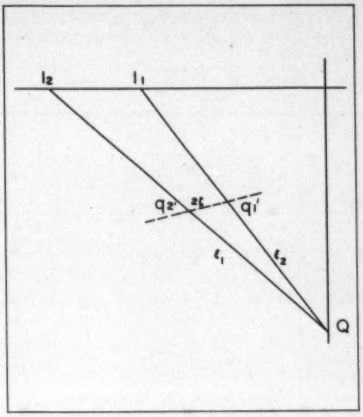

FIG. 8 – Arrangement of charges

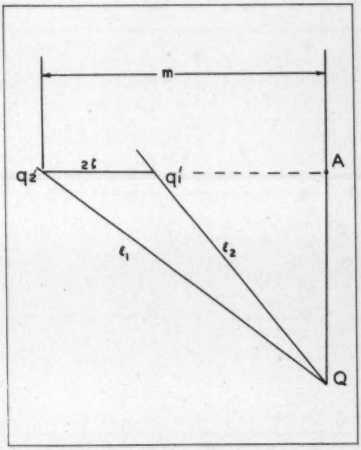

FIG. 9 – Assumed arrangement of charges

Considering now the two charges q_1' and q_2' and referring to *Jeans* [1925], we may write the potential, in general, as

$$V = \frac{-q_2'}{2\pi\sqrt{(x-m)^2 + y^2 + z^2}} - \frac{q_1'}{2\pi\sqrt{(x-[m-\zeta])^2 + y^2 + z^2}} \tag{9}$$

After expanding the radicals in this equation by the binomial theorem, and much subsequent algebra, we can write

$$V = \frac{\rho I}{2\pi} \cdot \left\{ \frac{(k^2a^2 + h^2 + xka) \cdot (\sqrt{(k-2)^2a^2 + h^2} - \sqrt{k^2a^2 + h^2})}{\sqrt{(k^2a^2 + h^2)^3}\sqrt{(k-2)^2a^2 + h^2}} + \frac{xa}{[(k-2)^2a^2 + h^2]\sqrt{k^2a^2 + h^2}} \right\} \quad (10)$$

Now, in the general case, we denote the distance from P to Q as d_i (really from P to A, as in Palmer). Also, then,

$$x_i = d_i \cos\theta; \quad (11)$$

where θ denotes the angle between the radius vector from the point P and the axis of the dipole, so that

$$V_P = \frac{\rho I r^3}{2\pi d_i^3} \cdot \left\{ \frac{(k^2a^2 + h^2 + d_i ka\cos\theta_i) \cdot (\sqrt{(k-2)^2a^2 + h^2} - \sqrt{k^2a^2 + h^2})}{\sqrt{(k^2a^2 + h^2)^3}\sqrt{(k-2)^2a^2 + h^2}} + \frac{d_i a\cos\theta_i}{[(k-2)^2a^2 + h^2]\sqrt{k^2a^2 + h^2}} \right\} \quad (12)$$

Now, for a dipole at Q, with

$$\cos\theta_i = \frac{b}{d_i} \quad (13)$$

we find

$$(V_P)_Q = \frac{\rho I r^3}{d_2^3} \cdot \left\{ \frac{(k^2a^2 + h^2 + bak) \cdot (\sqrt{(k-2)^2a^2 + h^2} - \sqrt{k^2a^2 + h^2})}{\sqrt{(k^2a^2 + h^2)^3}\sqrt{(k-2)^2a^2 + h^2}} + \frac{ab}{[(k-2)^2a^2 + h^2]\sqrt{k^2a^2 + h^2}} \right\} \quad (14)$$

It is now a simple task to add in all the potentials at P due to the current electrodes I_2 and I_1 and the image dipole at Q'. The total potential at P is, therefore,

$$V_P = \frac{\rho I}{2\pi} \cdot \left[\frac{1}{d_2} - \frac{1}{d_1} + r^3\left(\frac{1}{d_2^3} + \frac{1}{d_1^3}\right) \cdot \left\{ \frac{(k^2a^2 + h^2 + bak) \cdot (\sqrt{(k-2)^2a^2 + h^2} - \sqrt{k^2a^2 + h^2})}{\sqrt{(k^2a^2 + h^2)^3}\sqrt{(k-2)^2a^2 + h^2}} + \frac{ab}{[(k-2)^2a^2 + h^2]\sqrt{(k-2)^2a^2 + h^2}} \right\} \right] \quad (15)$$

This general result may be checked with the symmetrical case of Palmer by putting $k = 1$; thus we find

$$V_P = \frac{\rho I}{2\pi}\left[\frac{1}{d_2} - \frac{1}{d_1} + \frac{abr^3}{(a^2 + h^2)^{3/2}}\left(\frac{1}{d_2^3} + \frac{1}{d_1^3}\right)\right] \quad (16)$$

The potential differences between any two points may be calculated from Eq. (15) and numerical studies may be conducted as desired. Simplification to the two-dimensional problem is obvious. It may also be mentioned that the analysis of Palmer was compared with actual field measurements for a cylindrical cavity (a cave was the actual geological structure for which the field measurements were conducted). The agreement between theory and field measurements was very good.

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Some Studies on the Evaluation of Gummed-Paper Collectors Used in Determining Radioactive Fallout

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Abstract—Part of the study on the evaluation of the gummed-paper collector used in determining radioactive fallout is presented. Sampling under rainless conditions was examined quantitatively as a function of humidity, wind velocity, ultraviolet radiation, and storage time. It was found that sampling is a complicated function of wind velocity and humidity, with electrostatic effects as a dependent variable. Sampling during rain was found to be a function of the wettability of particulate matter, hydrophobic particles being readily deposited from raindrops. Some evidence is presented that the delayed radioactive fallout is hydrophilic or soluble in water or both.

Introduction—In 1951 the Atomic Energy Commission set up a world-wide network to monitor radioactive fallout from nuclear operations, particularly weapons testing in Nevada and in the Pacific Proving Grounds [*Eisenbud* and *Harley*, 1953, 1955, 1956]. One procedure used was to employ a sticky sheet of gummed paper to which would presumably adhere particles falling or impinging on its surface. This technique was not at the time evaluated for effectiveness because of time limitations. The extreme simplicity of placing this gummed paper, of mailing it, and of measuring its radioactivity was a strong inducement to employ this technique at a large number of stations and to continue this program in spite of known deficiencies in the system.

A complete evaluation of the gummed-paper method has been undertaken at the request of the Atomic Energy Commission to determine the efficacy of this monitoring procedure under varying environmental conditions. The results of a portion of the study are reported in this paper.

The debris resulting from a nuclear explosion varies according to the type of burst, and the quantities of material completely or partially vaporized differ appreciably. A ground burst produces particulate matter by condensation of the vaporized upper surface of the Earth's crust. Thus, an explosion in a desert vaporizes tons of sand and on a coral reef, tons of calcium carbonate. The particulate matter formed in such clouds differs therefore in size distribution, chemical composition, and surface properties of the particles. After the appearance of nuclei, particles grow slowly by condensation and probably much more rapidly by coagulation [*Stewart*, 1956]. From limited experimental results it was found that the presence of oxygen and, to a lesser degree, water vapor tends to reduce the particle size of metallic aerosols [*Werle* and *McCully*, 1954]. A certain equilibrium in size distribution is finally reached, and the particulate matter is subject to diffusion and sedimentation processes. Larger particles (several hundred microns in diameter) settle rapidly in the free atmosphere. Smaller particles (below one micron in diameter) remain suspended almost indefinitely in the absence of precipitation, because of the presence of turbulence in the atmosphere.

Experimental work—The problem of the evaluation of the gummed paper collector was divided into two parts: (a) sampling during dry weather; (b) sampling during precipitation (rain).

Sampling during dry weather—Sampling with gummed papers during dry weather is subject to the following variables: wind velocity and turbulence (wind structure), relative humidity, electrostatic charges on the papers and on the particles, temperature, and solar radiation. Therefore, the various effects of these factors were studied. In addition, the adherence of particles to the sticky surface was examined as a function of various types of gummed paper and of its storage time and the phenomenon of particle rebound from the gummed paper was investigated.

The following powders were used as tracers: NJZ 2266 and 2210 fluorescent pigments (d = 4.1 g/cc), calcium carbonate (d = 2.7 g/cc), and carbonyl iron (d = 7.9 g/cc). The size range of the fluorescent powders was 0.5–10 microns in diameter, of the calcium carbonate powder 1–35 microns in diameter (over 80 pct in the 1–10 micron range), and of the carbonyl iron 0.1–3 microns in diameter. The number of particles of fluorescent tracer per gram was determined by using a dilution photometric method [*Rosinski*, *Glaess*, and *McCully*, 1956]. Another photometric method, in which the proportionality between the intensity of fluorescent light and the number of particles is

determined, was used to find the number of particles of fluorescent tracer collected per square centimeter of gummed surface. The other tracers were analyzed by dilution-microscopic and microscopic methods and by chemical analysis.

Two types of gummed papers were used in the evaluation: Simon Adhesive (SA) produced in April 1955 and Kleen-Stik (KS) manufactured in November 1955. The KS paper was from a defective batch and was used as an example of a poor paper for comparison with a paper of good quality.

Continuous variation in turbulence and wind velocity made it difficult to evaluate papers experimentally in the free atmosphere. Therefore a low-velocity wind tunnel with a Reynolds number of 10^4–10^5 and isotropic turbulence was used.

Effect of time of storage at various temperatures—The gummed papers were stored for half a year from the date of receipt (February 1, 1956) at 5°C and at room temperature (21–35°C). Accelerated storage tests were performed at 35 and 75°C at low relative humidity. The effect of storage at room temperature was not significant. This was determined in wind tunnel tests in which the paper was mounted perpendicularly to the direction of the 10-mi/hr wind because it was found that under these conditions the experiments are not greatly affected by humidity and electrostatic effects are minimized.

Effect of ultraviolet radiation—Exposure to 0.01 watt hr/cm² of UV radiation (average for a clear midsummer day at Cleveland, Ohio) did not affect the particle capture. It was concluded, therefore, that the UV radiation energy to which the gummed surface is exposed during a summer day has no influence on its sampling properties.

Effect of humidity—A horizontal mounting was used to establish the relationship between relative humidity and particle capture. Fresh Simon Adhesive paper was tested at five different humidities with 2210 fluorescent tracer. The results are shown in Figure 1. The angle a is shown as the angle between the plate and the direction of the air flow measured clockwise from the plate. The capture of particles approaching horizontally was found to be much higher (a factor of 6) at a relative humidity of 15 pct than at one of 48 or 60 pct. The curve in Figure 1 indicates that particle capture is practically independent of humidity above 35 pct but that it changes rapidly (is inversely proportional) in regions of low humidity.

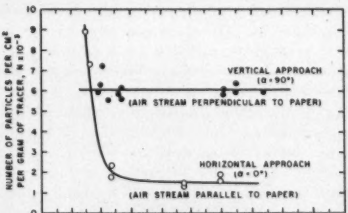
NUMBER OF PARTICLES PER CM² PER GRAM OF TRACER, N x 10⁻³
VERTICAL APPROACH (α = 90°)
(AIR STREAM PERPENDICULAR TO PAPER)
HORIZONTAL APPROACH (α = 0°)
(AIR STREAM PARALLEL TO PAPER)
RELATIVE HUMIDITY, PERCENT

FIG. 1 – Effect of humidity on capture of particles approaching horizontally and vertically

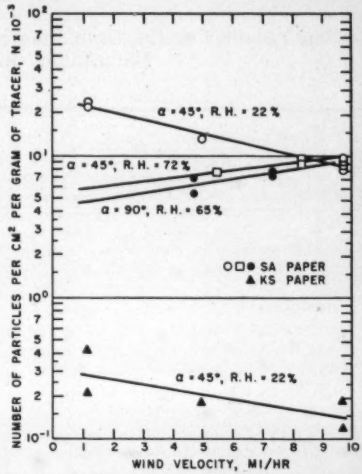
NUMBER OF PARTICLES PER CM² PER GRAM OF TRACER, N x 10⁻³
α = 45°, R.H. = 22 %
α = 45°, R.H. = 72 %
α = 90°, R.H. = 65 %
○□● SA PAPER
▲ KS PAPER
α = 45°, R.H. = 22 %
WIND VELOCITY, MI/HR

FIG. 2 – Effect of wind velocity on particle capture of NJZ 2210 tracer

Effects of wind velocity and electrostatic charges—Several experiments with both gummed papers were conducted to investigate the effects of the wind velocity on particle capture. The 45° mounting of plates was chosen for these experiments to combine the effects of deviation of particle trajectories from the streamlines of air flow and of electrostatic charges. The results are shown in Figure 2.

The results of experiments at a high humidity showed that the number of particles captured by the surface increases with rising wind velocity, which is in agreement with theory. The greater the inertia of the particle the greater the deflection from the trajectory of the air stream; thus, the

higher the wind velocity, the higher the number of particles collected at a given turbulence. On the other hand, it was found for both types of gummed paper at low humidities that the higher the wind velocity, the lower the particle capture.

The capturing mechanism at low humidities was assumed to be as follows: The paper exposed to wind develops certain electrostatic charge independent of the wind velocity in the experimental range. A particle approaching the sampling plate travels through the electrostatic field which attracts it with a given force, and a particle traveling in the direction of the wind has a certain inertia. Every particle, therefore, moves on a trajectory resulting from the two forces or two vectors acting on it. The vector representing the electrostatic field is constant. A change in the wind velocity vector results in a different angle of particle approach to the gummed surface, and the highest deflection toward the sampling plate is at lower wind velocities which give higher particle capture. It is emphasized that the effect of electrostatic forces is insignificant at velocities greater than 10 mi/hr. This is shown in Figure 2 where the number of particles captured per unit area is the same at both high and low humidities. The gummed-paper collector, therefore, samples independently of humidity at higher wind velocities in the presence of the inertia effect.

The deposit on the gummed surface examined in UV light revealed a definite sharp pattern for all tests at low humidities (15, 16, and 24 pct). At higher humidities (48 and 60 pct) the deposit was more uniform and did not show sharp edges in

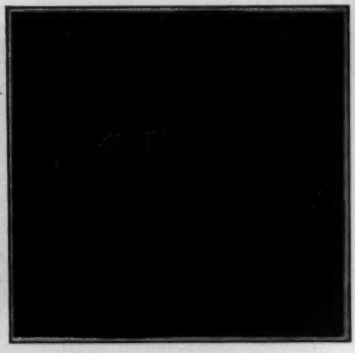

FIG. 3 – Deposit of fluorescent tracer collected at 15 pct relative humidity on SA paper (2×)

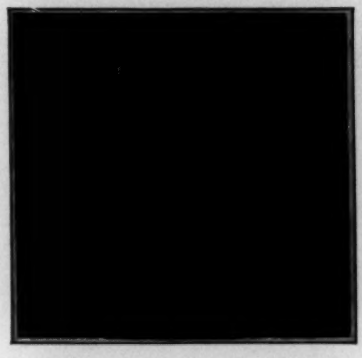

FIG. 4 – Deposit of fluorescent tracer collected at 48 pct relative humidity on SA paper (2×)

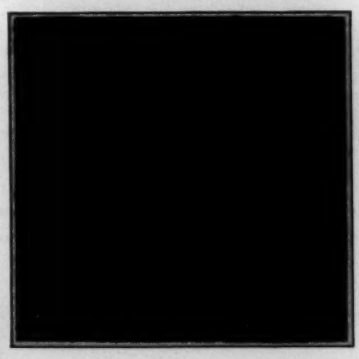

FIG. 5 – Deposit of fluorescent tracer collected at 75 pct relative humidity on SA paper (2×)

design. At 75 pct and in all tests in which an antistatic fluid was applied to the glossy side of a gummed paper, the deposit was uniform. This additional information explains the effect of humidity which influences formation of the electrostatic charge and, therefore, particle capture. The deposit on Simon Adhesive photographed in UV light is shown in Figures 3, 4, and 5.

Two tests were made to determine quantitatively the effects of electrostatic charges on sampling. In these tests two gummed films were mounted horizontally with sticky surfaces, 3 inches apart, facing each other. Particles suspended in an air stream (R. H. = 29 pct) moved horizontally

(α = 0°) at 720 ft/min. The particles were deposited on the lower plate because of electrostatic forces, turbulence, and sedimentation and on the upper plate because of electrostatic forces and turbulence with the sedimentation vector acting in the opposite direction. The results are shown in Table 1.

It was found that, for particles of one to ten microns in diameter, 86.7 pct of the captured particles were collected because of an electrostatic field and the turbulence of the air stream. It is believed that the electrostatic effect was predominant but a quantitative interpretation is, at present, impossible. The remaining 13.3 pct was collected by sedimentation.

In the absence of electrostatic forces the particle capture is a function of only particle inertia, wind velocity, turbulence, and the characteristics of the adhesive.

Rebound phenomenon—The microscopic examination of gummed paper bombarded with one- to three-micron particles revealed that not every particle that strikes the surface is collected. This so-called rebound phenomenon was observed with all types of powders and is a function of the paper.

TABLE 1 – *Effects of turbulence and electrostatic charges on particle capture by SA paper*

Number of particles per sq cm of paper		By settling		By turbulence and electrostatic charges	
Lower plate	Upper plate	N	pct	N	pct
614	464	75	12.2	539	87.8
715	509	103	14.4	612	85.6

It was possible to determine the difference in the scavenging properties of the two papers. The particle rebound from a Kleen-Stik paper surface was much more frequent than that from a Simon Adhesive paper surface. This introduced another uncertainty factor in the field sampling data.

The effect of foreign contamination on the rebound of particles from gummed paper was also examined and found to be a very complicated problem. Unreliable sampling results in the presence of large amounts of foreign particulate matter.

Sampling during precipitation—The experiments were performed with simulated and natural rain. Simulated rains were produced with raindrops of controlled size distribution and terminal velocity.

Simon Adhesive paper was used in all the tests. The experiments with rain were divided into four classes: (1) soluble substance on paper, clean rain; (2) insoluble particulate matter on paper, clean rain; (3) soluble substance in rain; (4) insoluble particulate matter in rain with (a) hydrophilic particles, and (b) hydrophobic particles.

Soluble substance on paper—The particulate matter which is deposited on the surface of the gummed paper during the sampling period may be partially soluble in water. Other soluble substances which were deposited earlier and left on the paper after the raindrops dried may also be present. The rain falling on the surface of the collector will dissolve some of this previously deposited soluble substance and wash it off the surface. These conditions were reproduced experimentally by using a soluble deposit on the gummed paper. The results of the experiments are given in Tables 2 and 3 and Figure 6.

TABLE 2 – *Size distribution of drops from simulated and natural rains*

Diameter d	Simulated rain				Natural rain					
	1		2		3		4		5	
	Number of drops	Pct	Number of drops	Pct	Number of drops	Pct	Number of drops	Pct	Number of drops	Pct
mm										
0–1	2	0.9	11	2.4	136	66.0	295	69.4	310	70.5
1–2	26	11.6	427	94.1	54	26.2	112	26.4	115	26.1
2–3	64	28.6	14	3.1	14	6.8	15	3.5	13	2.9
3–4	56	25.0	2	0.4	2	1.0	2	0.5	2	0.5
4–5	57	25.4	0	0	0	0	1	0.2	0	0
5–6	19	8.5	0	0	0	0	0	0	0	0
Total	224		454		206		425		440	
d_{av}, mm	3.4		1.5		0.93		0.86		0.83	
d_g, mm	3.1		1.5		0.76		0.71		0.70	

d_{av}—average diameter.
d_g—geometric mean diameter.

TABLE 3 – *Washout of soluble substances from SA paper by simulated and natural rains*

	Wind speed	Rainfall		Washed out	Retained
		Rate	Amount		
Simulated rain					
	mi/hr	in/hr	inch	pct	pct
1[a]	7	1.0	5.72	99.8	0.2
		1.0	3.66	99.9	0.1
		1.0	1.67	99.7	0.3
		1.0	0.80	99.5	0.5
		1.0	0.45	98.5	1.5
2[a]	7	0.4	0.52	99.8	0.2
		0.2	0.19	98.2	1.8
		0.2	0.10	48.4	51.6
		0.2	0.05	37.6	62.4
		0.2	0.03	15.8	84.2
Natural rain					
3[a]	7	0.32	0.32	99.1	0.9
4[a]	7	0.16	0.04	43.2	56.8
		0.16	0.05	30.1	69.9
5[a]	15	0.12	0.03	35.2	64.8

[a] Size distribution given in Table 2.

The experimental results with real and simulated rain are in good agreement. Because of differences in the two rains of drop size distribution, angle of the falling drops, and wind velocity, which may carry away fragments of the raindrops, four tests were run to demonstrate that the results obtained with simulated rains give a realistic picture of washout of soluble substance from gummed surface by rain.

Insoluble particulate matter on paper—Hydrophilic or hydrophobic particles collected on the gummed surface cannot be washed off by rain. Experiments were performed with dust containing large agglomerates. It was found that all single particles remain on the same spots but that agglomerates are broken up by the striking raindrops.

Soluble substance in rain—The particles which form in the course of an atomic explosion are scavenged by water droplets in clouds and by falling raindrops. This scavenging mechanism is rather complicated and is probably a function of several variables [*McCully* and others, 1956]. The soluble substance from the particles is completely or partially dissolved in rain water. A raindrop striking the gummed paper with terminal velocity may splash part of its contents. The splash effect is a function of raindrop size and the spot where the raindrop strikes the gummed-paper collector.

The results of the experiments are given in Figure 7. The results, of course, vary with raindrop size distribution. It is easily seen that the heavier the rainfall, the lower the retention efficiency due to the limited storage capacity of the gummed-paper collector.

Insoluble particulate matter in rain—Particles present in the atmosphere may be either hydrophilic or hydrophobic. Preliminary tests showed that there exists a great difference in the efficiency of the gummed surface in scavenging the two types of particulate matter.

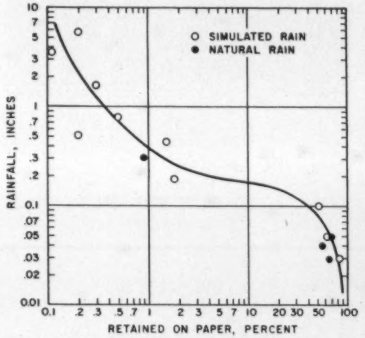

FIG. 6 – Washout of soluble substances from SA paper by simulated and natural rains

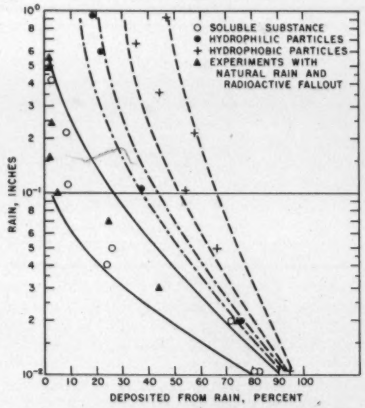

FIG. 7 – Retention of soluble substances and hydrophilic and hydrophobic particles present in rain by SA paper

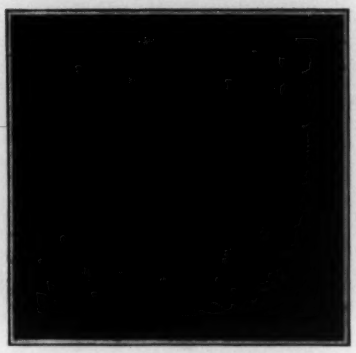

FIG. 8 – Imprints of raindrops containing hydrophilic particles on SA paper (0.5×)

Hydrophilic sols—Raindrops (4.4 mm diameter) containing insoluble hydrophilic particles both on the inside and on the surface leave imprints on the surface of gummed paper, as shown in Figure 8. In this figure the imprints were allowed to dry on the paper. The hydrophilic particles deposited can easily be washed off the surface by water before drying.

During a rainfall, gummed paper becomes covered with water. Raindrops, therefore, strike the water layer first. In penetrating the two-mm water layer, raindrops with hydrophilic particles do not deposit any dust on the gummed surface. The particles are suspended in water and may be lost by splashing during rain or in the water spilled when the paper on the stand is being changed. Experiments performed with simulated rain gave the results shown in Figure 7.

Hydrophobic sols—Hydrophobic insoluble particles from raindrops are readily deposited on the gummed surface. The imprints of raindrops falling perpendicularly onto a dry film surface are shown in Figure 9. The hydrophobic particles cannot be washed off the surface by water. They are entrapped and collected by the surface at the time of impact. Some of them float on the surface of the water present on the gummed paper. Also, during rainfall, when a two-mm water layer covers the surface, hydrophobic particles are readily deposited. The results of experiments with simulated rain are given in Figure 7.

Conclusions and summary—It is emphasized that the experimental results discussed in this paper describe the sampling mechanism of gummed papers only for particles of the materials used in the tests. The tracer was dispersed by a glass jet, and the electrostatic charge present on particles was unknown.

On the basis of the results of the wind-tunnel tests, it is possible to visualize the sampling mechanism of the gummed paper under dry conditions. Very small particles reach the sampling station by turbulent diffusion of the cloud in the free atmosphere. From this cloud only a small fraction is collected on the gummed paper due to settling and the random particle motion of Brownian diffusion. The rest are scavenged due to turbulence (particle inertia) and electrostatic forces. The quantity of dust collected by and on the gummed surface is a complicated function of wind velocity and humidity, which affect the formation of an electrostatic field. The paper, therefore, samples different numbers of particles from similar clouds under different meteorological conditions. The use of antistatic fluid may eliminate the variable caused by different electrostatic charges.

In sampling material scavenged by rain from the atmosphere, the sticky paper sampler has been shown to have a varying efficiency depending on a number of factors. Variations are introduced by the nature of particulate matter, that is, whether it is soluble, hydrophilic, or hydrophobic. High quantities of radioactive nuclides collected during rainfall might indicate a high proportion of hydrophobic particles. On the other hand, daily observations of collections during rainfall actually indicated that the collected radioactive material from the delayed fallout is soluble in water or hydro-

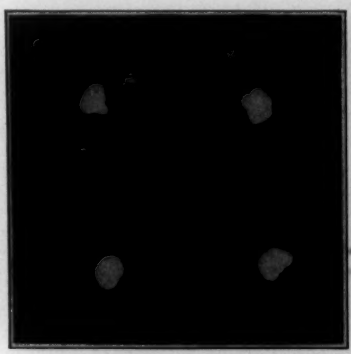

FIG. 9 – Imprints of raindrops containing hydrophobic particles on SA paper (0.5×)

TABLE 4[a] – *Data from gummed paper sampling during 24-hr rainy periods or single showers*

Date	Amount of rainfall	Radioactivity, disintegrations per minute							Retention
		Stand							
		1	2	3	4	5	6	Aver.	
	inch								pct
Sep. 10–11	0.02	709.4	389.3	1643.0	1209.0	627.8	331.4	815.3	75.0
Sep. 8–10	0.03	689.1	285.2	712.6	692.4	769.3	1138.0	714.4	43.7
Sep. 15–17	0.07	758.0	1523.0	735.0	675.0	1005.0	846.0	926.1	24.4
Aug. 25–27	0.10	338.0	311.8	290.3	222.2	140.0	355.8	276.3	5.1
Aug. 23–24	0.16	117.2	145.3	93.4	154.7	155.4	...	133.2	1.5
Aug. 30–31	0.24	...	474.0	401.9	315.1	398.8	...	397.4	3.0
Sep. 5–6	0.49	414.0	244.2	463.5	321.8	494.0	422.5	396.7	1.5
Aug. 18–20	0.56	593.3	413.3	657.3	448.0	494.1	647.5	542.3	1.8

[a] [*Rosinski*, 1957].

philic or both. As an example, the results of sampling in Chicago under conditions of low atmospheric contamination are given in Table 4. It was assumed that the concentration of radioactive material in the atmosphere was approximately constant during the sampling period. Deposition of contaminants under dry conditions did not vary appreciably for this period of time. The concentration of radioactive fallout in rain was calculated from 0.02 inch of rain with 75 pct retention, assumed for the paper. The results plotted on the graph fall into the region corresponding with retention efficiency of soluble substances present in rain. It was concluded therefore that the radioactive particulate matter present in the rain was soluble in water or hydrophilic or both, because the curve for hydrophilic particles shifts toward the soluble substance region when the water present on the paper is poured off prior to sending it for analysis. Hydrophobic particles are only very slightly affected by this procedure as they are deposited readily on the gummed surface during rain.

The accumulation of radioactive debris in soil can be only semiquantitatively predicted from the extremely simple and rapid gummed-paper method. It must be kept in mind, however, that the amount of radioactive material which will be found in soil for places with low humidities, for example, Albuquerque, N. M., and Grand Junction, Colo., should be smaller than the quantity predicted from the gummed paper results. On the other hand, the prediction for places with heavy rainfall, for example, Binghamton, N. Y., and Philadelphia, Pa., should be too low, contribution to soil being much higher than estimated from sampling.

The above studies have led to the conclusion that a different sampler is required in order to obtain consistent and reliable data for estimation of the contribution of radioactivity from fallout under dry conditions and during rain storms. It must be emphasized that the amount of radioactive material stored in the soil can be determined by soil analysis only, and therefore the sampling of soils and natural vegetation should be continued.

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A Note on the Spectra of Wind Waves

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Abstract—Attention is drawn to a useful non-dimensional parameter which allows the width of the energy spectrum of waves to be taken into account in predicting some of their statistical properties. This parameter is evaluated for the spectra of wind generated waves proposed by Darbyshire and by Neumann, and is found to modify the usual statistical formulas to considerable extent. The high-frequency attenuation due to wave-measuring instruments is also shown to have an important effect.

Introduction—Many of the commonly used formulas for the statistical properties of waves depend on the assumption that their spectrum is confined to a narrow band of frequency, [see for example *Longuet-Higgins*, 1952]. It has been shown in a recent paper, however [*Cartwright and Longuet-Higgins*, 1956] that such formulas can be modified to allow for an energy spectrum of arbitrary shape by the use of a single parameter ϵ, denoting the 'spectral width.' This note studies the properties of the two proposed forms of the spectrum of wind waves in the light of this concept.

Definitions—Let $E(\sigma)$ be the spectrum of energy density with respect to (positive) angular frequency σ of, say, the height of the sea surface above a fixed point, assumed to be representable by the sum of an infinite number of sinusoidal components in random phase relation. If m_n is the nth moment of $E(\sigma)$ about the origin

$$m_n = \int_0^\infty \sigma^n E(\sigma)\, d\sigma \qquad (1)$$

The spectral width parameter is then defined by

$$\epsilon = [(m_0 m_4 - m_2^2)/m_0 m_4]^{\frac{1}{2}} \qquad (2)$$

It can be shown that since $E(\sigma)$ is essentially positive ϵ must lie between 0 and 1, and when small is proportional to the ratio of rms (root mean square) spectral width to mean frequency.

The probability distribution of wave crests above, or troughs below, the mean level is then given by

$$p(\eta) = \frac{1}{(2\pi)^{\frac{1}{2}}} e^{-\frac{1}{2}\left(\frac{\eta^2}{\epsilon^2}\right)} + \tfrac{1}{2}(1-\epsilon^2)^{\frac{1}{2}}\eta e^{-\frac{1}{2}\eta^2}\left[1 + \operatorname{erf}\left(\frac{1-\epsilon^2}{2\epsilon^2}\right)^{\frac{1}{2}} \cdot \eta\right] \qquad (3)$$

where η is (crest height)/$(m_0)^{\frac{1}{2}}$, and $m_0^{\frac{1}{2}}$ is the rms fluctuation of the wave surface. The mean crest height, which is exactly equal to half the mean crest-to-trough height is

$$\left[\frac{\pi}{2}(1-\epsilon^2)m_0\right]^{\frac{1}{2}}$$

and the rms crest height, which is in general greater than half the rms crest-to-trough height, is

$$[(2-\epsilon^2)m_0]^{\frac{1}{2}}$$

Another useful property, enabling ϵ to be estimated without actually computing the spectrum itself, is that the ratio of the number of zero crossings to the number of turning values over a long section of wave record has the expectation.

$$(1-\epsilon^2)^{\frac{1}{2}}$$

The narrow spectrum formulae are of course as above with ϵ set equal to zero. Other statistical properties also are discussed in *Cartwright* and *Longuet-Higgins* [1956].

Spectral width of wind waves—It is of interest to consider what range of values of ϵ may be expected from wind waves at sea. Since the spectrum narrows as waves travel from the generating area, owing to dispersion, we may in general expect to find the maximum values of ϵ within the fetch, though superimposed swell from other storm centers may widen the spectrum outside this region. The spectrum of waves produced by a steady wind has yet to be formed on an *a priori* basis, but empirical forms based on observations have been proposed independently by *Darbyshire* [1955], and *Neumann* [1953]. *Roll* and *Fischer* [1956] have also suggested a modification to Neumann's result.

Darbyshire's empirical spectrum for deep water and infinite fetch is given as

$$H_T = \begin{cases} 0.0036[U^{\frac{1}{2}} - 0.43T]T^4 & 0 < T < U^{\frac{1}{2}}/0.43 \\ 0 & T > U^{\frac{1}{2}}/0.43 \end{cases} \qquad (4)$$

where $\frac{1}{4}\ H_T^2(\text{ft}^2)$ is the mean square fluctuation due to wave components with periods within

$\pm\frac{1}{2}$ second of T, U the 'gradient wind speed' in knots and T the wave period in seconds. The equivalent value of $E(\sigma)$ is obtained from

$$E(\sigma) = \frac{1}{8} H_T^2 \left| \frac{dT}{d\sigma} \right| \tag{5}$$

where $T = 2\pi/\sigma$, which can be arranged in the form

$$E(\sigma) = \begin{cases} A\sigma^{-7}[(BV/g)^{\frac{1}{2}} - \sigma^{-\frac{1}{2}}]^2 & \sigma > (BV/g)^{-1} \\ 0 & \sigma < (BV/g)^{-1} \end{cases} \tag{6}$$

where $A = 0.73$ ft^2/sec^8, $B = 3.9$ sec, and V is the 'surface wind speed' ($= \frac{3}{2}U$) in the same units as g, the acceleration due to gravity.

Calculation of ϵ from (1), (2), and (6) gives the remarkable result that

$$\epsilon = \frac{(11)^{\frac{1}{2}}}{5} = 0.665 \tag{7}$$

independently of the wind speed, or indeed of any of the arbitrary constants included in the formula.

The spectrum proposed by Neumann for a fully arisen sea is, in our notation

$$E(\sigma) = D\sigma^{-6} \exp(-2g^2/V^2\sigma^2) \tag{8}$$

D being constant, independent of wind speed, and equal to 27 ft^2/sec^5, though *Walden* [1954] has suggested that this constant is too high. Calculation from (1), (2), and (8) gives

$$\epsilon = \left(\frac{2}{3}\right)^{\frac{1}{2}} = 0.816 \tag{9}$$

again independently of the constants employed.

Roll and Fischer's modification of Neumann's spectrum is effectively to multiply (8) by σ and adjust the constant suitably. However, the 4th moment of such a spectrum is infinite ($\epsilon = 1$), and so this case cannot profitably be discussed here.

Mean wave height—Since the mean wave height is $(1 - \epsilon^2)^{\frac{1}{2}}$ times the value obtained by ignoring ϵ, it is immediately obvious from the above figures that estimates of the mean wave height deduced from the appropriate spectrum using the narrow spectrum formula will be seriously in error.

For example, using Darbyshire's result, the narrow spectrum formula should be multiplied by $(14)^{\frac{1}{2}}/5 = 0.748$ to give the true mean wave height, while the factor appropriate to the Neumann spectrum is $(\frac{1}{2})^{\frac{1}{2}} = 0.577$. These factors, particularly the second, may seem surprisingly drastic, but it should be remembered that the true mean is the mean of all waves present whereas the definition used by Pierson and Neumann (see for example *Pierson* [1954]) includes only the dominant waves, ignoring the secondary waves which correspond to 'negative maxima.' In fact Pierson shows that with a Neumann spectrum $(1 - 3^{-\frac{1}{2}})$ or 42 pct of the total number of true waves may be ignored. With such a system the 'mean wave height' would be considerably larger than the true mean crest-to-trough height deducible theoretically from the spectrum.

Assuming that Neumann's formula gives a correct value for wave energy density, the fact that this can be related to the mean wave height as defined by Pierson and Neumann by the narrow spectrum formula appear to be largely fortuitous.

The definition of mean wave height is clearly one of importance. That used in this article has the advantages of being objective and immediately applicable to theory, although it may be difficult to derive from purely visual observations.

It is outside the scope of this note to compare the wave heights and periods predicted by the above, and other formulas. A full comparison of Neumann's spectrum with observations from other sources and with prediction formulae not involving spectra is given in the papers by *Walden* [1954] and by *Roll* and *Fischer* [1956].

Instrumental attenuation—The value of ϵ given by Neumann's spectrum is particularly high, and values measured from typical wave records are almost always lower and nearer to the value obtained from Darbyshire's spectrum. However, it should be remembered that all wave-measuring instruments, with the exception of a vertical capacitance—or resistance—wire type, impose an attenuation curve on the short wave length part of the spectrum, thus artificially narrowing the spectrum, and in general decreasing the value of ϵ. For example, suppose waves with a spectrum given by (8) were measured with the shipborne wave recorder on which Darbyshire's measurements were based. This instrument is roughly equivalent to a pressure recorder ten feet below the mean surface, and thus it attenuates the shorter wave lengths much less than a pressue gauge on the sea bed. The apparent spectrum would be

$$E(\sigma) = D\sigma^{-6} \exp(-2g^2/V^2\sigma^2 - 2h\sigma^2/g) \tag{10}$$

[see *Neumann*, 1955], h in this case being ten feet. This spectrum has moments of the form

$$m_n = D \int_0^\infty \sigma^{n-6} \exp(-P\sigma^{-2} - Q\sigma^2)\, d\sigma$$

$$= D \left(\frac{P}{Q}\right)^{\frac{1}{4}(n-5)} K_{\frac{1}{2}(n-5)}(2\sqrt{PQ}) \tag{11}$$

where $K_p(z)$ is a modified Bessel function of the second kind. By making use of the property that for a positive integral p,

$$K_{-p-\frac{1}{2}}(z) = K_{p+\frac{1}{2}}(z) = (-1)^p \left(\frac{\pi}{2} z\right)^{\frac{1}{2}} \frac{d^p}{dz^p}\left(\frac{e^{-z}}{z}\right) \quad (12)$$

we can obtain ϵ in the following simple form

$$\epsilon = \left[\frac{2+x}{3+3x+x^2}\right]^{\frac{1}{2}} \quad (13)$$

$$\text{with } x = 2(PQ)^{\frac{1}{2}} = 4(gh)^{\frac{1}{2}}/V$$

For some typical wind speeds, (13) gives the following figures:

$$V = 60 \text{ ft/sec: } \epsilon = 0.63$$

$$V = 40 \text{ ft/sec: } \epsilon = 0.57$$

$$V = 20 \text{ ft/sec: } \epsilon = 0.46$$

These values are nearer to the constant 0.665 deduced from Darbyshire's spectrum, and are in fact in the range of spectral widths commonly associated with use of this wave-recorder. This might suggest that Darbyshire's formula underestimates values of $E(\sigma)$ at the high frequency end of the spectrum, and that the spectral width of newly generated waves may in fact be closer to that deduced from Neumann's formula. It should, however, be remembered that Darbyshire's spectrum is an extrapolation for values of σ greater than about 1 sec^{-1}. At any rate it may be concluded that a wave-recorder subject to attenuation at the higher frequencies may be expected to give 'spectral widths' within quite a limited range for most conditions of locally generated waves.

Conclusion—On the whole, it is clear that the magnitude of ϵ is by no means negligible, and that its value is essential to the complete statistical specification of sea conditions. Its measurement would therefore be a desirable addition to the parameters normally recorded by collators of wave data and such similar quantities as ship motions and microseisms.

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Wind Influence on a Rotary Tidal Current

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Abstract—At Amrum Bank in the German Bight the tide rotates counterclockwise, with the major current axis in the direction SE-NW. This rotary tidal current is strongly influenced by the direction of the prevailing wind. Not only is the center of the current ellipse displaced by the variation in velocity and direction of the residual current, but the ellipse itself is greatly deformed. The major and minor axes vary in size, the symmetry of the ellipse changes, and considerable phase differences occur. The actual tidal current under the influence of both the displacement of the center and the deformation of the tidal ellipse varies greatly with a change in the direction of the wind.

In a previous paper [*Mandelbaum*, 1955] the observational data [*Deutsche Seewarte*, 1924–1933], which form the basis for the present study were discussed and the results regarding the residual current presented. In order to calculate the Fourier coefficients of the tide-current function which best approximate the given values, the 24 computed Moon half-hour means M_n had to be weighted because for some wind directions, especially from the NE-sector, the number of observations for strong winds is small. As this involves a large amount of numerical calculation, the computations were carried out by an electronic digital computer. Five Fourier coefficients were calculated: A_0, which represents the residual current; A_1, B_1, the coefficients of the M_2-tide; and A_2, B_2, the coefficients of the M_4-tide. The selection of data according to prevailing wind conditions causes an increase of the mean error of the M_n, and hence A_3, B_3 coefficients would represent only computational results without real value. Tidal current ellipses were calculated which show the currents under winds blowing from eight different wind directions. In order to accentuate wind influences, tidal current ellipses were also calculated for winds with forces 5 or higher on the Beaufort scale.

The mean tidal currents—A total of 20,768 current observations was used for the analysis of the mean tidal currents at Amrum Bank Lightship. The 24 Moon half-hour means M_n represent, therefore, in the average between 800 and 900 observations (Table 1, column 2). The observed values of current velocities were resolved into two rectangular components, a NW^+ -SE^- component, and a NE^+-SW^- component. These directions rather than N and E components were chosen because inspection showed that the major axis of the tide current ellipse could be expected to be in a NW-SE direction. Columns 3 and 6 contain the 24 Moon half-hour means M_n for both components. They represent the average velocity of the current during 1/24 of the time between one Moon meridian transit and the next, taken as 31 min. Since the length of the period between two successive Moon-transits varies between 12h 19m and 12h 34m, an error is introduced by taking a Moon half-hour uniformly as 31m. But since the error is compensated to a great part during a full month, and the maximum deviation from the mean of 12h 25m is not very frequent, the great advantages gained for the compilation of the data for analysis justify this simplification. The mean M_n can be considered as representing the observed current at the middle of each half-hour, that is, M_1 represents the current 15m after Greenwich Moon-transit.

The Fourier coefficients calculated for these M_n are given at the lower part of Table 1. The current velocities C_n computed with these coefficients are found in columns 4 and 7. In columns 9 and 10 are given velocity and direction of the resultant current of the C_n. The directions of column 10 as well as those given in the other tables are not corrected for magnetic variation. The average magnetic declination at Amrum Bank during the 10-year period 1924–1933 was 9°W. Figure 1 shows the mean tide-current ellipse at Amrum Bank constructed with the current vectors of columns 9 and 10 of Table 1. The strongest current occurs between the Moon half-hours 4 and 5 at 02h 00m Moon time after Greenwich Moon transit. (All time data and time intervals in the text and the tables are given in Moon hours. One Moon hour is 1/12 of the time between two successive Moon transits. 00h 00m is the time of Moon transit at Greenwich.) It has a velocity of 42.7 cm/sec in the direction 320° magnetic = 311° true (clockwise from N). This represents the ebb current. The strongest current in the opposite direction, the flood current, occurs 7h 47m after

TABLE 1 – *Mean tidal current*

Moon half hour n	Number of observations	NW component: Current velocity, Observed M_n	NW component: Current velocity, Computed C_n	NW component: Deviation $M_n - C_n$	NE component: Current velocity, Observed M_n	NE component: Current velocity, Computed C_n	NE component: Deviation $M_n - C_n$	Current vector: Velocity V	Current vector: Direction d (magnetic)
1	2	3	4	5	6	7	8	9	10
		cm/sec	cm/sec		cm/sec	cm/sec		cm/sec	°
1	877	29.6	28.9	0.7	8.7	9.0	−0.3	30.3	332
2	905	35.4	35.3	0.1	8.0	8.3	−0.3	36.3	328
3	889	39.8	39.8	0.0	7.7	6.8	0.9	40.4	325
4	896	42.6	42.1	0.5	5.0	5.0	0.9	42.2	322
5	863	41.8	42.2	−0.6	3.0	2.8	0.2	42.2	319
6	879	39.3	40.0	−0.7	0.1	0.4	−0.3	40.0	316
7	879	33.8	35.3	−1.5	−1.6	−1.7	0.1	35.3	312
8	872	28.2	28.8	−0.6	−3.4	−3.4	0.0	29.0	308
9	847	20.2	19.4	0.8	−4.5	−4.2	−0.3	22.2	303
10	869	10.0	9.1	0.9	−4.6	−4.6	0.0	10.2	288
11	838	−0.4	−1.8	1.4	−3.9	−4.2	0.3	4.6	202
12	846	−11.4	−12.5	1.1	−2.9	−3.3	0.4	12.9	150
13	861	−23.8	−22.1	−1.7	−1.7	−2.0	0.3	22.2	140
14	861	−31.9	−29.7	−2.2	−0.7	−0.5	−0.2	29.7	136
15	895	−35.7	−34.6	−1.1	0.9	0.8	0.1	34.6	134
16	862	−35.6	−36.5	0.9	1.5	2.0	−0.5	36.6	132
17	900	−34.4	−35.4	1.0	2.7	3.2	−0.5	35.5	130
18	845	−29.5	−31.2	1.7	4.8	4.2	0.6	31.5	127
19	870	−24.4	−24.7	0.3	5.9	5.1	0.8	25.2	123
20	840	−16.9	−16.4	−0.5	6.3	6.0	0.3	17.5	115
21	832	−9.1	−7.0	−2.1	6.6	7.0	−0.4	9.9	90
22	838	2.3	2.9	−0.6	7.3	8.0	−0.7	8.5	25
23	825	12.1	12.6	−0.5	9.2	8.6	0.6	15.2	349
24	879	22.7	21.3	1.3	9.0	9.1	−0.1	23.2	338
A_0		4.36			2.64				
A_1 B_1		25.60; 30.02			5.45; −3.38				
A_2 B_2		−0.87; −1.65			0.88; 0.94				

Greenwich transit. It sets in a direction 131° magnetic = 122° true at a velocity of 36.8 cm/sec. The reason that the two directions are not directly opposite each other is, of course, found in the influence of the residual current A_0, which sets to the NNW (Fig. 1, OC). The angle between the directions of the ebb and flood currents is 193°, convex to the SW.

The average V of the velocity of the maximal incoming and outgoing current, which can be considered as a measure of the strength of the tidal current, is V = 39.7 cm/sec. If we disregard the residual current and take C (Fig. 1) as the center of the ellipse, the maximal velocities of the ebb and flood currents are 38.4 cm/sec and 41.6 cm/sec respectively; the directions of the maximal currents are 316° (307° true) and 136° (127° true) respectively, which is the direction of the major axis of the tide-current ellipse.

Since the axis is closely in the NW-SE direction,

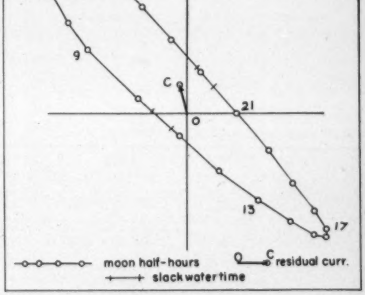

FIG. 1 — Mean tide-current ellipse

we define as time of slack water the time when the current sets to the NE or SW. This definition is slightly arbitrary, but it has the advantage of giving values for beginning and end of flood or ebb current which are mutually comparable under all conditions produced by different wind conditions. Slack water between ebb and flood occurs 05h 10m after Greenwich transit. Slack water in the reverse direction occurs 05h 25m later. If we eliminate the effect of the residual current the corresponding times of slack water are 05h 00m and 10h 52m after Greenwich transit respectively. The tide is rotating counterclockwise, changing from NW over SW to SE, and from SE over NE to NW. A characteristic of the tide ellipse is its acuteness at the period of flood. Compared to this the other end of the tide current ellipse, representing the ebb, is rather blunt. The four quadrants of the current ellipse are not swept through by the current vector in equal time intervals as can be seen from Table 2. Neither is any half of the ellipse swept through in equal times. From maximal ebb-current (NW) to maximal flood current (SE) takes 5h 47m. The reverse period from flood to ebb current is 6h 13m, a time difference of nearly one-half hour. Currents with NW-components (ebb) run for 6h 35m as against 5h 25m for currents with SE-components (flood). The outgoing current runs 1h 10m longer than the incoming current. Even when we disregard the influence of the residual current, there is still a difference of 16 min in favor of the ebb current. This difference compensates for the stronger currents in the SE direction.

Tidal currents at winds from eight different wind directions—All observational data were divided

TABLE 2 – *Time table for the mean tide-current ellipse*

Current direction	Current without residual						Current with residual					
	Time		Time intervals				Time		Time intervals			
			Quadrants		Maximum to max.	Minimum to min.			Quadrants		Maximum to max.	Minimum to min.
	h	m	h	m	h m	h m	h	m	h	m	h m	h m
NW	02	00			. .		02	00			. .	
			3	00					3	10		
SW	05	00			5 47	. .	05	10			5 47	. .
			2	47					2	37		
SE	07	47			. .	5 52	07	47			. .	5 25
			3	05					2	48		
NE	10	52			6 13	. .	10	35			6 13	. .
			3	08					3	25		
NW	02	00			. .	6 08	02	00			. .	6 35
			3	00					3	10		
SW	05	00			. .		05	10			. .	
Difference					0 26	0 16					0 26	1 10

TABLE 3 – *Fourier coefficients of the tidal current at eight different wind directions*

Wind direction	NW component					NE component				
	A_0	A_1	B_1	A_2	B_2	A_0	A_1	B_1	A_2	B_2
E-ESE	9.4	27.8	28.8	−2.8	−4.3	0.1	6.6	−3.3	0.4	0.8
SE-SSE	8.8	23.6	29.0	−1.6	−1.5	4.3	6.4	−3.8	0.8	1.1
S-SSW	7.8	24.1	29.5	−1.3	−1.2	7.8	5.4	−3.2	0.7	0.7
SW-WSW	4.4	26.3	29.6	−3.2	−3.5	7.8	4.4	−3.3	0.2	1.3
W-WNW	1.2	26.6	31.3	−1.3	−0.4	4.4	5.8	−3.3	0.3	0.6
NW-NNW	−1.0	25.9	31.3	−0.9	−0.6	−1.5	5.8	−2.5	1.1	0.8
N-NNE	2.2	24.7	30.8	−1.1	−1.5	−4.0	5.4	−2.2	0.5	0.8
NE-ENE	4.3	26.7	30.0	−1.7	−1.7	−3.6	5.0	−3.1	2.4	2.4
Mean Current	4.3	25.6	30.0	−0.9	−1.6	2.6	5.5	−3.4	0.9	0.9

into eight groups according to the direction of the wind blowing at the time of the observation. The tidal currents were analyzed for the eight wind-direction groups. From all data those made at wind forces 5 and up of the Beaufort scale were selected, and the tidal currents developing at strong winds blowing from eight different directions were also computed. The results of this latter analysis will be used to verify trends revealed by the analyses of all observations.

Table 3 shows the Fourier coefficients of the NW and NE components of the tidal currents at winds from eight different directions. Table 4 shows the velocities and directions of the current vectors calculated on the basis of these coefficients. These values are plotted in Figure 2. An analysis of both Table 4 and Figure 2 reveals a wind influence on the velocity and direction of the tide-current not only by a displacement of the center of the tide-current ellipses but also by a change of the form of the ellipse and a phase difference of corresponding points in various ellipses.

Form of the tidal ellipses (without residual current) —The direction of the major axis does not vary significantly from the direction of the mean tidal ellipse of 316°. However, the maximal current velocity that is in direction of the major axis, varies considerably from the values for the mean current (Table 5, columns 2, 3, 4, and Fig. 3). The mean ebb current not considering the influence of the residual current has a velocity of 38.4 cm/sec in the direction of the major axis. The smallest velocity for the ebb current is found at S-winds with 36.2 cm/sec, the strongest at W-wind with 40.5 cm/sec. The smallest velocity for the flood current is also found at S-winds, while the strongest is found at E-winds with 44.1 cm/sec. The greatest difference between the velocity of the incoming and that of the outgoing current is 7.5 cm/sec found at E-winds; the smallest difference is 1.1 cm/sec at winds blowing from the NW-sector. But the asymmetry of the ellipse in the direction of the major axis, that is, strongest current to SE, is nowhere reversed (Fig. 4); the difference SE-velocity minus NW-velocity remains always positive.

We consider as the minor axis of the current ellipse a line segment passing through the end point C of the residual current vector in a NE-SW direction bounded by the perimeter of the current ellipse. Its length represents the width of the ellipse. It varies from a smallest value at SW-WSW winds, where the minimal current velocity is 5.8 cm/sec, and a largest value at NE-ENE winds,

TABLE 4 – *Velocity and magnetic direction of tidal current at winds from eight different directions*

Moon half-hour	E-ESE		SE-SSE		S-SSW		SW-WSW		W-WNW		NW-NNW		N-NNE		NE-ENE	
	v	d	v	d	v	d	v	d	v	d	v	d	v	d	v	d
n	cm/sec	°	cm/sec	°	cm/sec	°	cm/sec	°	cm/sec	°	cm/sec	°	cm/sec	°	cm/sec	°
1	35.1	327	32.8	336	33.6	339	30.2	339	28.5	337	24.6	328	32.0	319	29.5	323
2	39.6	325	38.4	331	39.2	335	35.0	335	35.0	331	31.4	324	35.4	317	35.8	321
3	43.1	322	42.6	328	43.2	331	39.0	332	39.7	327	36.2	320	37.2	316	40.2	319
4	45.2	319	44.9	324	45.6	328	41.6	329	42.1	324	38.8	317	40.0	314	42.6	315
5	45.9	316	45.5	321	45.7	325	42.6	326	41.3	322	38.9	314	40.6	311	43.2	311
6	45.2	313	43.6	318	43.5	323	41.2	324	39.1	319	36.5	310	36.7	310	41.4	307
7	41.2	310	39.3	315	38.8	321	37.4	322	33.9	316	31.6	306	34.7	304	37.1	301
8	34.6	306	32.9	311	32.0	319	30.7	320	26.0	313	24.5	299	28.4	298	30.8	294
9	26.4	300	24.4	306	23.2	318	21.4	319	16.1	308	16.1	286	20.6	288	22.8	283
10	16.4	287	13.9	298	12.9	319	10.2	320	4.9	283	9.2	248	12.9	263	14.4	260
11	7.9	239	5.0	268	2.5	346	2.4	104	8.3	153	10.9	180	10.6	209	10.9	207
12	12.0	171	7.6	156	8.7	122	14.7	126	19.5	141	19.7	156	17.0	170	17.4	164
13	22.0	151	16.3	140	17.9	125	25.3	127	29.2	137	28.5	149	25.2	156	24.9	150
14	30.1	145	23.5	134	25.3	124	33.5	126	36.4	135	35.6	143	32.2	149	31.9	143
15	34.3	140	28.3	131	30.1	124	38.4	125	40.9	133	40.1	141	36.9	145	36.2	140
16	33.9	137	30.0	128	32.1	122	39.2	124	41.9	131	42.1	139	38.9	143	37.5	139
17	31.7	135	29.0	125	31.2	120	37.0	120	40.1	128	41.1	138	37.9	142	35.6	139
18	25.3	131	25.4	121	27.9	116	31.5	116	35.9	125	37.4	137	31.9	141	31.0	140
19	16.8	125	19.9	113	22.9	108	24.5	109	29.6	121	31.4	135	27.6	140	24.2	142
20	7.7	103	14.4	95	17.0	93	17.0	94	22.4	113	23.4	132	19.6	139	15.7	144
21	6.3	12	9.7	59	13.0	63	12.2	61	15.0	96	14.6	125	10.3	137	6.3	150
22	14.3	341	12.6	10	14.1	24	13.2	20	10.5	59	5.5	94	0.8	51	3.6	132
23	22.5	333	18.8	351	19.7	359	18.5	357	12.8	10	7.4	353	9.0	323	12.9	321
24	29.3	329	25.9	341	26.8	346	24.6	346	19.1	349	16.0	334	18.0	321	21.8	322

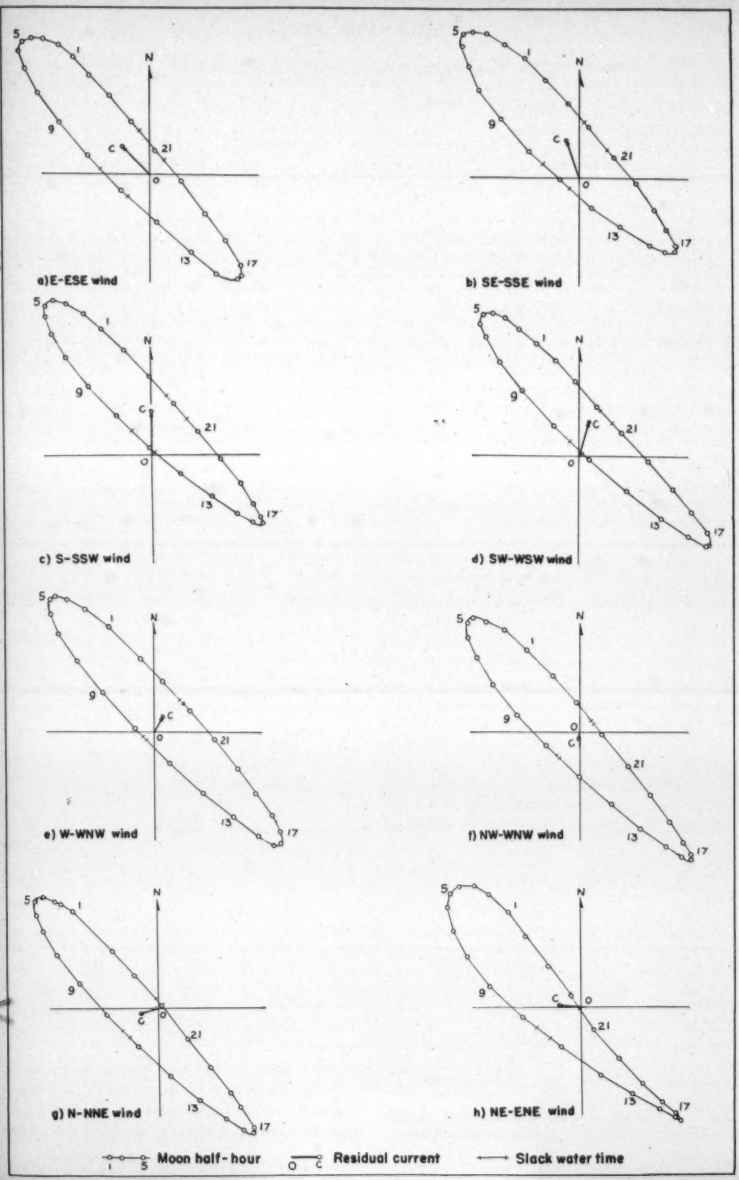

FIG. 2—Tide-current ellipses for eight different wind directions

TABLE 5 – *Tide-current without residual current*

Wind direction	Maximal current									Minimal current					
	Velocity				Direction of axis, magnetic	Time				Average velocity	Slack water time				Duration of flood-curr.
	To NW	To SE	Average	Diff.		To NW	To SE	Diff.			Ebb → flood		Flood → ebb		
1	2	3	4	5	6	7		8		9	10	11		12		13	
	cm/sec	cm/sec	cm/sec		°	h	m	h	m	h m	cm/sec	h	m	h	m	h	m
E-ESE	36.4	44.1	40.2	7.5	317	2	15	7	30	5 15	7.5	4	55	10	35	5	40
SE-SSE	36.6	39.3	37.9	2.7	316	2	15	7	50	5 35	7.7	4	55	10	50	5	55
S-SSW	36.2	39.2	37.7	3.0	316	2	10	7	40	5 30	6.5	5	00	10	55	5	55
SW-WSW	37.5	42.6	40.0	5.1	315	2	10	7	50	5 40	5.8	4	55	10	40	5	45
W-WNW	40.5	42.9	41.2	2.4	317	1	55	7	50	5 55	6.7	4	50	10	55	6	05
NW-NNW	40.1	41.1	40.5	1.1	318	2	00	7	50	5 50	6.8	5	00	10	55	5	55
N-NNE	37.9	40.8	38.9	2.9	317	2	10	7	50	5 40	6.1	5	00	10	55	5	55
NE-ENE	39.2	41.4	40.3	2.2	316	2	00	7	45	5 45	8.0	4	55	10	45	5	50
Mean Curr.	38.4	41.6	40.0	3.2	316	2	00	7	45	5 45	6.9	4	55	10	50	5	55

where the minimal current velocity is 8.0 cm/sec (Table 5, column 10). Generally speaking, the current ellipse is wider at winds from the NE-sector than that at winds from the SW-sector. This might be caused by the proximity of the coast line to the E.

A very strong deviation from the mean form of the tidal ellipse is found at NE-ENE winds (Fig. 2g). The curve becomes very blunt at the NW end and extremely pointed at the SE end. It is not immediately clear why winds from this sector should have such an accentuating effect. But the same type of curve results from an analysis of currents under the influence of strong winds from that direction (Fig. 5) where even a tendency for the development of an overlapping figure-eight curve can be recognized at the SE end.

A very peculiar but persistent dislocation of the tide-current ellipse seems to develop under the influence of strong winds (Beaufort 5 and up).

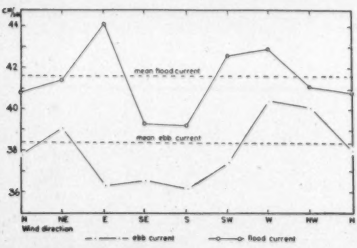

FIG. 3 — Velocity of maximal tide-current (without residual current) with various wind directions

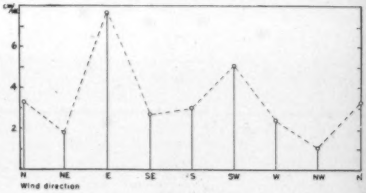

FIG. 4 — Velocity difference between maximal flood and ebb current (without residual current)

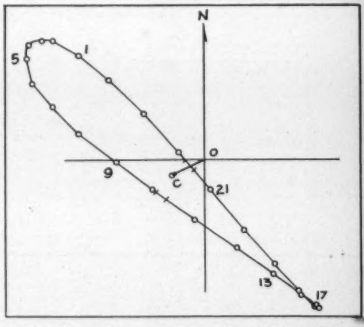

FIG. 5 — Tide-current ellipse at strong NE-ENE winds

Figure 6 shows the current ellipses at strong winds from the S to NW in comparison with the ellipses calculated on the basis of observation of all winds from that direction. In each case the major axis is

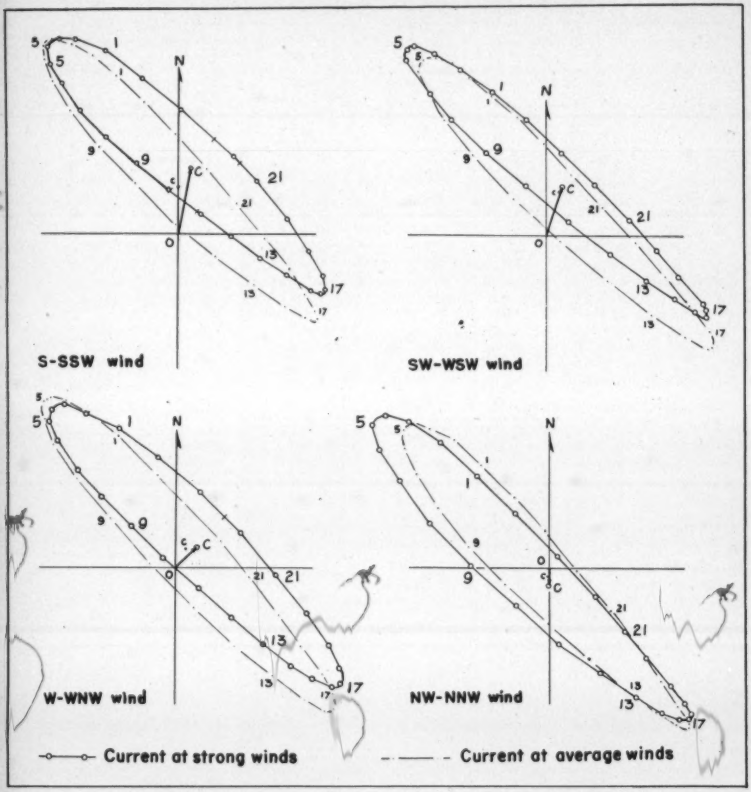

FIG. 6—Comparison of tide-current ellipses at strong winds with those at average winds

rotated by about four degrees in a counterclockwise direction from the mean direction.

Tidal current ellipse with residual currents—Much more pronounced, of course, are the changes in the current if we consider the total influence of the wind on the current, without eliminating the residual current. The displacement of the current ellipse by adding the residual current is indicated in Figures 1, 2, and 5 by a vector OC starting at the origin O of the NS and EW coordinates. The endpoints C mark the center of the current ellipse without residual current. The velocity and direction of the vectors OC are given in Table 6. Figure

TABLE 6—*Residual current for eight wind directions*

Wind direction	Component		Resultant	
	NW	NE	Velocity	Direction, magnetic
	cm/sec	cm/sec	cm/sec	°
E-ESE	9.4	0.1	9.4	316
SE-SSE	8.8	4.3	9.8	314
S-SSW	7.8	7.8	11.0	0
SW-WSW	4.4	7.8	8.9	29
W-WNW	1.2	4.4	4.6	15
NW-NNW	−1.0	−1.5	1.7	191
N-NNE	2.2	−4.0	4.6	254
NE-ENE	4.3	−3.6	5.6	275

TABLE 7 – *Current composed of tide-current and residual current*

Wind direction	Maximal current					Minimal current									
	Velocity		Direction, magnetic			Velocity		Time				Duration			
	Ebb	Flood	Ebb	Flood	4 – 5	Ebb → flood	Flood → ebb	Ebb → flood		Flood → ebb		Flood		Ebb		12 – 11	
1	2	3	4	5	6	7	8	9		10		11		12		13	
	cm/sec	cm/sec	°	°	°	cm/sec	cm/sec	h	m	h	m	h	m	h	m	h	m
E-ESE	45.9	34.4	316	139	177	−9.0	5.0	05	25	10	05	4	40	7	20	2	40
SE-SSE	45.6	30.0	321	127	194	−3.8	10.0	05	25	10	25	5	00	7	00	2	00
S-SSW	45.7	32.1	325	123	202	2.0	12.7	05	20	10	25	5	05	6	55	1	50
SW-WSW	42.6	39.3	326	124	202	1.5	11.2	05	10	10	25	5	15	6	45	0	30
W-WNW	42.1	41.9	323	130	193	−2.5	10.3	04	55	10	50	5	55	6	05	0	10
NW-NNW	38.9	42.1	315	139	176	−8.0	4.0	04	55	11	00	6	05	5	55	−0	10
N-NNE	40.6	38.9	312	142	160	−10.0	0.8	05	05	10	45	5	40	6	20	0	40
NE-ENE	42.4	36.6	313	139	173	−11.0	−0.7	05	05	10	35	5	30	6	30	1	00
Mean Current	42.7	36.8	320	131	189	−4.6	7.5	05	10	10	35	5	25	6	35	1	10

Negative velocity at minimal current indicates SE direction.

2 shows that the origin O of the current vectors lies outside the ellipse for winds from S to WSW and for winds from NE to ENE. While in general the current swings in a counterclockwise fashion, for S to WSW winds the slack-water current from ebb to flood swings clockwise from NW over NE to SE. Similarly for NE-ENE winds the slack-water current from flood to ebb swings clockwise from SE over SW to NW. At strong winds of 5 Beaufort and up, winds blowing from the N-NNE sector also cause a clockwise swing of the slack-water current from flood to ebb. At all other wind conditions the counterclockwise rotation as it exists at the mean tidal current is maintained: the slack-water current swings from ebb to flood over SW and from flood to ebb over NE, both ways counterclockwise. Of course, the current velocities at both times of slack water show a considerable inequality as can be seen from Table 7, columns 7 and 8.

However, more significant than the velocity is the phase of the slack-water current. The times of slack water from one direction to the other are shown in columns 9 and 10 of Table 7. At W to NNW wind slack water from flood to ebb current occurs 15 min earlier than at the mean tidal current, namely 4h 55m after Greenwich transit. At E and SE winds it occurs 10 min later than normally, namely 5h 25m after Greenwich transit. At the reversal from flood to ebb current the difference in slack water time is even greater, ranging from 10h 05m at E-ESE winds, 30 min earlier than at the mean current, to 11h 00m at NW-NNW winds, 25 min later than the time of mean slack current (Fig. 7). The duration of the flood current is shortest at E-ESE winds, 4h 40m and longest at

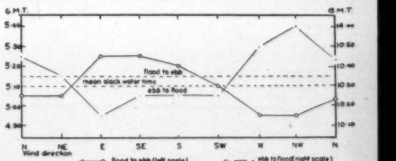

FIG. 7 — Slack water time (with residual current) with various wind directions

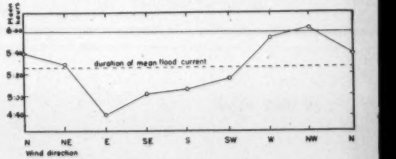

FIG. 8 — Duration of flood current (with residual current) with various wind directions

NW-NNW winds, 6h 05m. In Figure 8 is shown the duration of the incoming tide current for the eight different wind directions. At E-ESE winds the ebb current runs more than 1¼ times as long as the flood current. At winds from the W to NNW sector the times are nearly equal.

A similar picture is shown by the velocity of the maximal current in the NW and SE directions (Table 7, columns 2 and 3; see also Fig. 9). The wind direction that causes longer duration of the tide current in one direction causes also stronger velocities in the same direction. Strongest ebb currents run at E, SE, and S-winds, which are the

wind directions which in Figure 8 show the shortest duration of the flood current. On the other hand, strongest flood currents run at W and NW-winds, which at the same time cause the longest duration of the flood current.

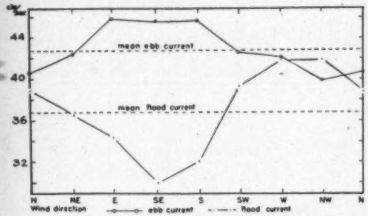

FIG. 9 — Velocity of maximal current (with residual current) with various wind directions

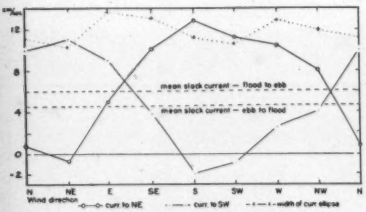

FIG. 10 — Velocity of the slack current (with residual current) with various wind directions

The times of maximal current velocities do not vary significantly whether we consider the current ellipse with or without the residual current. However, the directions of the maximal current are not opposite to each other if we consider the currents as they actually are, without eliminating the residual current. At winds from SE to WNW the two directions form angles of more than 180° convex to the SE, with the greatest deviation of 22° from a straight angle occurring at S to WSW winds (Table 7, column 6). At winds from N-NNE the angle between the two directions is concave to the SE with a deviation of 20° from a straight angle. At winds from other directions the deviation of the angle from 180° amounts to only a few degrees. At the mean current the deviation is 9° convex to the SE.

In Figure 9 we compare the variation of the maximal velocities of the current. It can, of course, be expected that the currents in opposite directions show opposite variation. Where one increases in velocity the current in the opposite direction decreases in velocity. This relationship is more or less regular. However, the curves of the maximal currents show no symmetry for the velocities in opposite directions. The flood current shows a maximal variation of 12 cm/sec, which is 29 pct of the maximum current velocity. It also has a very pronounced minimum at SE-SSE winds. In contrast to that, the ebb current has a much smaller maximal variation of only 6 cm/sec, which is only 13

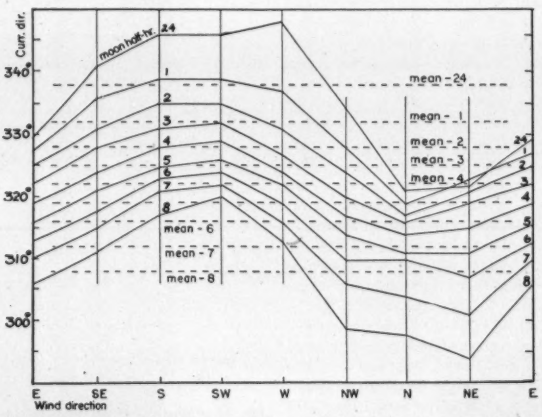

FIG. 11—Directions of the current (with residual current) during ebb with various wind directions

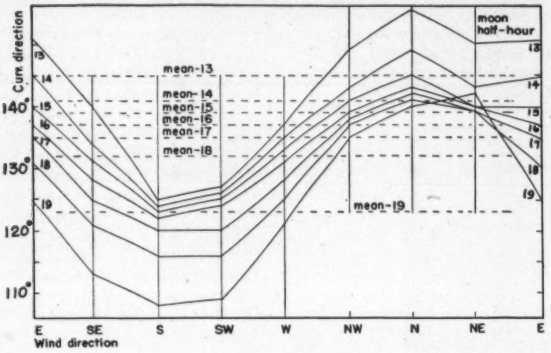

FIG. 12—Directions of the current (with residual current) during flood with various wind directions

pct of the maximum velocity. Moreover, the maximum at SE-SSE wind is flat, remaining at equal height from E to SSW.

Figure 10 shows the variation of the velocity of the slack current. The curves are more or less symmetrical to each other; winds that increase the current velocity in one direction decrease it in the opposite direction. This would indicate a mere consequence of the dislocation of the center of the ellipse due to the wind. However, the width of the ellipse also varies as indicated by the dotted curve. Winds from E and W increase the minor axis, while those from N and S decrease it. Figures 11 and 12 show the variation due to wind influence of the directions of the current running at the same Moon half-hour. The plotted data are the current directions tabulated in Table 4. Winds from the S-sector delay considerably the arrival of the counterclockwise rotating ebb current at a certain given current direction as compared to the mean time. Those from the N-sector advance the time of arrival at that direction. For instance at the Moon half-hour 24 the mean current runs in the direction 338° (horizontal line marked Mean-24). But at S-SSE winds the current is running in a direction 346°, 8° behind schedule, so to speak. At N-NNE winds on the other hand, the current runs at that time already in the direction 321°, that is, 15° ahead of schedule. This picture is prevailing during the whole period of ebb current (plotted for Moon half-hours 24 to 8).

The opposite is true for the flood current. Winds from the S-sector advance the arrival time at a certain current direction, while those from the

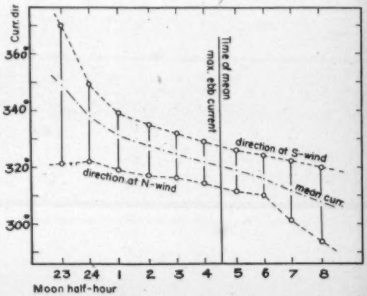

FIG. 13 — Maximal variation of the current directions (with residual current) during ebb

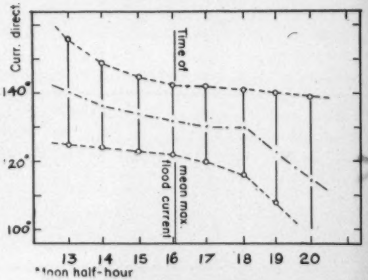

FIG. 14 — Maximal variation of the current directions (with residual current) during flood

TABLE 8 — *Difference in current directions (magnetic) for opposite wind directions without residual current*

Moon half-hour	Wind directions										Differences					
	N	S	Diff N-S	E	W	Diff. E-W	SE	SW	NW	NE	7–8	7–9	7–10	8–9	8–10	9–10
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	°	°		°	°		°	°	°	°						
1	327	329		331	329		334	326	331	332	8			−5	−6	
2	325	326		327	324		328	323	326	328	5				−5	
3	323	322		323	321		324	321	322	325					−4	
4	321	319		319	318		319	319	319	319						
5	317	317		315	316		316	316	316	315						
6	315	313		312	312		312	312	312	311						
7	310	308		307	308		306	309	308	305					4	
8	305	303		301	303		300	304	303	298	−4				6	5
9	296	292	4	290	292		288	296	292	284	−8	−4	4	4	12	8
10	267	263	4	254	248	6	253	284	268	250	−29	−15	3	16	34	18
11	183	183		181	171	10	199	184	179	179	15	20	20	5	5	3
12	155	155		156	152	4	160	152	152	149	8	8	11			5
13	146	146		146	145		148	144	146	141	4		7			5
14	141	141		143	142		142	139	141	136			6			4
15	139	138		139	139		139	137	139	135			4			
16	137	136		137	137		136	136	137	134						
17	136	135		135	134		134	133	136	133						
18	134	133		132	132		132	132	134	133						
19	132	130		128	130		128	129	132	133		−4	−5		−4	
20	128	125		120	125	−5	122	124	128	132		−6	−10	−4	−8	−4
21	118	115		97	113	−16	110	109	119	125		−9	−15	−10	−16	−6
22	71	72		19	77	−58	60	27	79	53	33	−19	13	−52	−26	26
23	352	358	−6	345	0	−15	2	340	357	344	22	−5	18	−17	−4	13
24	342	347	−5	335	348	−13	341	331	338	335	10		6	−7	−4	

Differences given if significant; that is, larger than three degrees.

N-sector delay it. For instance at the Moon half-hour 19 the mean current runs in a direction 123° (horizontal line marked Mean-19). But at S-SSE winds it runs already in a direction 108°, while at N-NNE winds it is 17° behind schedule and runs in the direction 140°.

The interval of directions within which the current varies under the influence of the wind is also variable. It is smallest at the time of maximal current both for the ebb and flood current. The interval becomes larger towards the time of slack current. In Figures 13 and 14 the intervals of variance are plotted for a few Moon half-hours before and after maximal ebb and flood current. At maximal ebb current the variance is 15°, at maximal flood current 21°. The cause of this considerable variation in the time for the current flowing in a given direction is two-fold: (a) the displacement of the center of the current ellipse by the variation of the residual current, and (b) the variation of the form of the ellipse and the change in the phase of the currents due to direct wind influence. Table 8 shows the direction of the tidal current during a tidal period for the main opposing wind directions after elimination of the effect of the residual current. These values were read with a protractor from Figure 2. When we compare the directions of the current at N and S winds (columns 1 and 2) (those directions which according to Figures 11 and 14 show extreme variations) we see that both tidal ellipses are nearly congruent

TABLE 9 — *M_2-tide current ellipse*

Wind direction	Semi-major axis *a*	Semi-minor axis *b*	Direction (magnetic) of max. current *d*	Time of max. current *t*
	cm/sec	cm/sec	°	Greenwich interval h m
E-ESE	39.4	6.3	316	1 46
SE-SSE	40.1	7.0	318	1 56
S-SSW	37.3	7.4	317	1 56
SW-WSW	38.1	6.2	316	1 52
W-WNW	39.6	5.5	316	1 54
NW-NNW	41.9	6.6	317	1 55
N-NNE	40.7	6.1	318	1 57
NE-ENE	39.5	5.6	317	1 53
Total	40.2	5.9	317	1 54

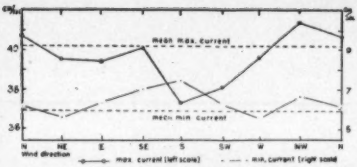

FIG. 15 — Variation of maximal and minimal velocity of the M_T-tide current

(column 3). However, when we compare the current ellipses at E and W winds (columns 4 and 5) we find considerable phase differences (column 6). These are significantly large during slack-water time. Winds from the E delay the rotation of the current from ebb to flood current and speed up the rotation from flood to ebb current. The same tendency we recognize when we compare currents at SW and NW winds (column 14) and at SW and NE winds (column 15). Delay in slack-water phase from ebb to flood we find also in columns 13 and 16. The other differences shown in the columns 11 to 16 are not so consistent. Nevertheless, the variation in the direction of the current for the same Moon-time can be considered partly caused by a direct deformation of the tide-current ellipse by the wind. Partly, and in most cases to a greater extent, it is caused by the dislocation of the center of the current ellipse by the varying residual current.

In order to determine how much the first order members of the harmonic analysis are influenced by the wind, the size and direction of the axes of the M_T-tide current ellipse were calculated [*Sendner*, 1952]. The tabulated values are found in Table 9. The maximal current is strongest at NW-NNW winds, weakest at S-SSW winds, with a maximal difference of 4.6 cm/sec or approximately ten per cent of the average maximal current. However, there is a secondary maximum at SE-SSE winds. The minimal values found between the maxima are also asymmetric (Fig. 15). The minor axis of the current ellipse also shows variations in length with a smallest value at W-WNW winds, 5.5 cm/sec, and largest at S-SSW winds, 7.4 cm/sec. Figure 15 shows that at S-SSW winds the major axis of the M_T-current ellipse is smallest, while the minor axis is largest, that is, the eccentricity of the current ellipse is smallest at S-SSW winds.

Summary—The result of the analysis brought out the following facts:

The rotary tide current at Amrum Bank shows a tide-current ellipse with a major axis in SE-NW direction. The minor axis is comparatively small. The rotation is in the mean counterclockwise. The direction of prevailing winds influences clearly the development of the tide-current ellipse, aside from the superimposed wind-driven part of the residual current. At winds from the S sector the major axis is smaller and the minor axis longer than normal. At winds from the NE sector the tide current ellipse is completely deformed with the SE part becoming pointed, or even overlapping.

Profoundly different from normal are the variations of the current ellipse if we consider the actual current, the tide-produced and wind-produced current superimposed upon each other. Then the current does not always rotate in a counterclockwise fashion. The times of slack water between ebb and flood and vice versa vary greatly and consequently the duration of ebb and flow. The maximal currents do not run in opposite directions. The angles differ as much as 20° from 180° either convex to the NE or to the SW.

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Flood Frequency by Regional Synthesis

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Abstract—Design of highway bridges in California has been predicated on waterways required for 30-yr to 100-yr floods. Determination of such floods is highly speculative because of relatively short stream-flow records. Longer records for an average stream of a hydrologically homogeneous region have been synthesized by combining nondimensional peak discharges, so as to derive factors for extrapolation of frequency curves for each stream of the region.

Reliability of the method, depending upon definition of homogeneity of a region, was tested by a graphical comparison. The test was devised by hypothesizing a 'perfect' 1000-yr flood record and dividing it by chance distribution into 20 50-yr records. Superimposed frequency graphs of these 20 hypothetical records gave a visual measure of disparities to be expected in natural records of comparable streams.

The paper, illustrated by charts, briefs the development of the graphical test, describes the application to one region in California, and shows similar results in a second region of entirely different character.

Introduction—This paper presents a purposeful and practical solution to the problem of extrapolating flood-frequency functions as a part of the economic design of waterways for highway bridges and culverts. The problem will first be defined in general terms by stating the policy of the California Division of Highways for design of waterways and describing the hydrology available for a solution.

Small waterways for culverts are specified in the publication *California Culvert Practice* [1955], in terms of floods of two frequencies. The ten-year flood determines the size of the culvert entrance, which must pass such a flood without head. The 100-yr flood determines design of the culvert barrel and appurtenances.

Bridge waterways are specified variously according to function. For a detour or temporary location, provision for only a ten-year flood may be considered adequate. The usual standard for permanent locations is the 30-yr flood. Higher standards of 50-yr and 100-yr floods are warranted for heavily traveled freeways or unilinear routes. If the historical flood is greater than the specified design frequency, it is always considered, generous provision being made to minimize backwater damage to upstream property. For any of these floods the bridge clearance provides a driftway above the waterway.

These references to a 10-yr, 30-yr, 50-yr or 100-yr flood, generalized as an n-yr flood, mean the momentary peak discharge likely to be equalled or exceeded once in n years. Floods of any desired frequency can be computed from past records of measured streams and estimated by analogy or indirect methods for unmeasured streams.

Accuracy of such computations is low. The basic data for any method of analysis is a statistical population of momentary peaks. Each item is an estimate, derived by extrapolating a stage-discharge relation or surveying a channel after a flood, usually with a probable error greater than five per cent. Short records are an unreliable sample. Long records begin with less reliable data obtained from periodic observations on staff gages.

Plots of recorded data attempt to relate peaks to frequency of occurrence. Typical plots exhibit a consistent relation among the more frequent small floods and a wild scatter of points representing less frequent great floods. The scatter is caused partly by the greater probable error in measuring great floods, but largely by the uncertainty of the frequency assumed for the plotting.

To understand the uncertainty of frequency, suppose there are 500 streams for which peaks have been recorded for 20 yr. For each stream the greatest peak would be plotted as a 20-yr flood, it being the maximum recorded in that period. If it occurred near either end of the 20-yr period, it might be considered the maximum in two consecutive 20-yr periods, and plotted as a 40-yr flood. Hydrologists are not agreed on the best plotting position, but all formulas known to the authors would call for plotting between these limiting positions at 20 and 40 yr.

However, if weather had been entirely random over the region and throughout the period of record, the 10,000 annual peaks equal to or exceeding

20-yr floods should include about 100 peaks equal to or exceeding 100-yr floods, 10 exceeding 1000-yr floods, and one of the order of a 10,000-yr flood.

On the other hand, 61 of the 500 streams would not have had even a 10-yr flood in the 20 yr. The following table summarizes the statistical distribution of frequencies of the 500 so-called 20-yr floods:

Frequency years	Number of floods
1–5	6
5–10	55
10–20	118
20–40	122
40–100	108
100–1000	83
1000–10000	7
10000+	1

Considering these inaccuracies of measurement and uncertainty of plotting frequency, it is a waste of time to take the data at face value and develop

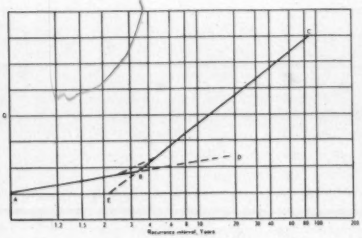

Fig. 1 – Typical bilinear graph

frequency functions by least-squares adjustment or other precise methods. Such an adjustment might derive the five-year flood with better accuracy but the more important 100-yr flood with a 99 pct error. The methods of this paper are based on visual adjustments, with reasoned speculation on distribution of infrequent floods.

An unpublished paper by the senior author [*Rowe*, 1953], presented at the 1953 meeting in Palo Alto, described the application of regional synthesis to compute precipitation-intensity frequency. The synthesis of a long record by combination of short records in a climatically homogeneous region was not new. Novelty in this application was the method of defining homogeneity. This analysis has been completed by Royce, and results have been published in the revised edition of *California Culvert Practice.*

When the same principle of synthesis is applied to flood peaks, the magnitudes of floods must be reduced to a common dimension independent of basin area, and a new test for homogeneity is necessary because of the hydrographic features of catchment basins. These two phases of the problem will be developed separately.

Common dimension of flood peaks—A flood peak is expressed in cubic feet per second (cfs) passing a certain measuring section on a stream. For comparison, peaks recorded on different streams or at different sections on the same stream are reduced to unit discharge, expressed in cfs per square mile, but such unit discharges are notably larger for small basins and certainly not independent of area.

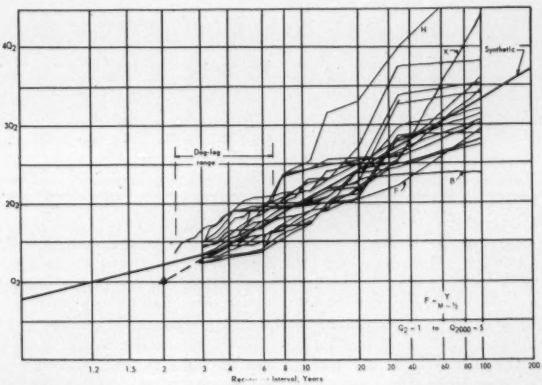

Fig. 2 – Synthetic frequency chart

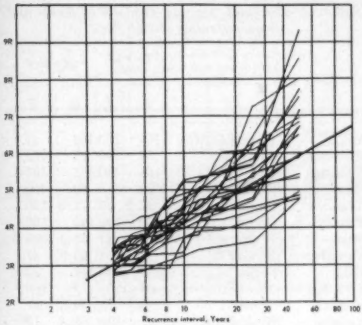

Fig. 3 – Random sampling, $F = Y/M$

Many hydrologists have resorted to a non-dimensional measure of floods by dividing discharges by a basic or fundamental discharge. All floods for any station are then expressed by their ratios to this base discharge. The mean annual flood and the one-year flood are conventional bases.

Neither of these is acceptable for California streams because the annual floods are a mixed assortment from several causes and not a random assortment from a single cause. This is evident from the typical bilinear or dogleg graph on probability paper (Fig. 1).

The bilinear ABC is the resultant of two independent linear series AD and EC, obtained by selecting each year the larger item. Theoretically the resultant should be a curve asymptotic to AD and EC, but for short records the curve is a poorly defined transition near the intersection B. Conversely, the appearance of bilinear graphs in frequency studies implies a mixture of two or more incongruent series.

Since the upper limb of the bilinear graph is of paramount interest for our purpose, the base discharge should be the best-defined point on that limb. The angle point between limbs is between three and four years on the frequency scale for long records and ranges from 1.5 to seven years for the shorter records. We adopted the five-year flood for our base, specifying that it be determined by intersecting the visual best-fit line on the upper limb with the abscissal line for five-year recurrence.

Non-dimensional procedure—Accordingly, each flood peak is expressed by its ratio to the five-year flood for the station. Our interest is limited to floods for which this ratio exceeds unity. The pro-

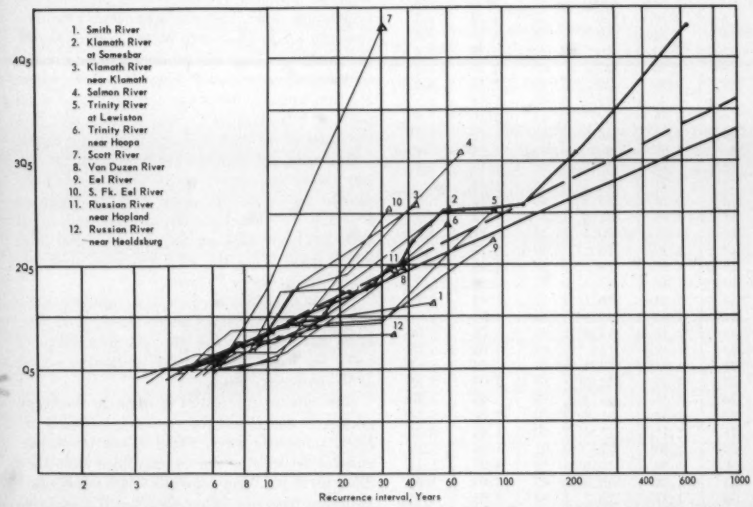

Fig. 4 – Synthesis of flood-peak frequency for 12 river stations in northwestern California, 1910–1956

cedure consists of the following steps: (1) Define a region of homogeneity; (2) From this region, select gaging stations likely to combine with unbiased analogy; (3) Construct a frequency graph for each station; (4) Determine the five-year flood for each station, using the upper limb of bilinear graphs; (5) For each station, express all floods as multiples of the five-year flood, by ratios R defined by $Q_i = R_i Q_5$; (6) Assemble the several sets of R in one synthetic set and arrange in descending order of magnitude; (7) Construct a frequency graph for this synthetic record as tho it were observed in a period of N yr, where N is the sum of the periods of record of the combined stations; (8) Determine visually a best-fit line for the well-defined part of the graph, giving little if any weight to wild points at the infrequent end; (9) Transfer the slope of this line to each of the separate station graphs.

Test for homogeneity—The mathematically elegant test for homogeneity would be a specification defining maximum departures of skewness and kurtosis as functions of period of record, but a graphical test is more eloquent.

In applying any such test, it is essential that the analyst realize the effect of pure chance on the scatter of points on a frequency chart. Figure 2 will be used to illustrate the principle. It was constructed around a typical bilinear projection on probability paper, with the upper limb extending from $Q_5 = 1$ to $Q_{2000} = 5$. With a perfect record, this could have been plotted from a 1000-yr record by the plotting formula $F = Y/(M - 1/2)$, where F is the tentative frequency in years of an annual peak; Y is the length of record in years, and M is the order of the peak counting from the greatest.

Reversing the hypothetical procedure, the top 300 annual momentary peaks which would have plotted such a perfect curve above a dogleg at $F = 3.34$ were listed on slips of paper and mixed with 700 blank slips representing the lower limb of the graph. Then the 1000 slips were dealt like cards into 20 lots of 50 items.

Each of these lots was considered a random 50-yr record for the station and plotted by the same rule. Each has the same five per cent probability of being the record observed over a random period of 50 consecutive years.

Now observe the scatter of these 20 frequency graphs. B and H are the extremes, but each exhibits a linearity which would be considered reliable for determining the ten-year flood altho they differ by 25 pct. Many analysts would not hesitate to project them to a 100-yr flood, but H would give double the solution by B.

TABLE 1 – *Plotting points for first 65 items of a synthesized 314-yr record of annual peak discharges*

Order of magnitude M	Ratio to Q_5 R	$\frac{314}{M-\frac{1}{2}}$ X	Order of magnitude M	Ratio to Q_5 R	$\frac{314}{M-\frac{1}{2}}$ X
1	4.28	628	33	1.26	9.7
2	3.08	209	34	1.25	9.4
3	2.58	126	35	1.24	9.1
4	2.54	90	36	1.23	8.8
5	2.53	70	37	1.21	8.6
6	2.52	57	38	1.20	8.4
7	2.38	48	39	1.18	8.2
8	2.23	42	40	1.18	8
9	1.98	37	41	1.16	7.8
10	1.98	33	42	1.15	7.6
11	1.88	30	43	1.14	7.4
12	1.80	27.3	44	1.14	7.2
13	1.77	25.1	45	1.14	7
14	1.76	23.2	46	1.13	6.9
15	1.76	21.6	47	1.12	6.7
16	1.71	20.3	48	1.11	6.6
17	1.59	19	49	1.10	6.5
18	1.55	18	50	1.10	6.3
19	1.46	17	51	1.08	6.2
20	1.44	16.1	52	1.08	6.1
21	1.42	15.3	53	1.05	6
22	1.42	14.6	54	1.05	5.86
23	1.39	14	55	1.04	5.75
24	1.38	13.4	56	1.04	5.65
25	1.36	12.8	57	1.03	5.55
26	1.34	12.3	58	1.03	5.46
27	1.32	11.8	59	1.02	5.37
28	1.31	11.4	60	1.02	5.28
29	1.30	11	61	1.01	5.19
30	1.30	10.6	62	1.01	5.11
31	1.28	10.3	63	1.01	5.02
32	1.27	10	64	1.01	4.94
			65	1.00	4.86

TABLE 2 – *Computed five-year and 100-yr floods and frequency rating of 1956 flood*

River	Station	Periodic floods		1956 flood	
		Q_5	$\frac{2}{3}Q_{20}$	Q	F
Smith	Crescent City	104	250	165	17
Klamath	Somesbar	80	190	202	125
Klamath	Klamath	165	400	425	135
Salmon	Somesbar	26	63	80	400
Trinity	Lewiston	28.5	69	71.6	120
Trinity	Hoopa	80	190	190	100
Scott	Ft Jones	9	22	38.5	1000+
Van Duzen	Bridgeville	22	53	43.5	37
Eel	Scotia	243	590	541	50
S Fk Eel	Miranda	68	165	173	130
Russian	Hopland	30	73	59.4	37
Russian	Healdsburg	51	120	65.4	10

Q is discharge in 1000 cfs; F is recurrence period in yr.

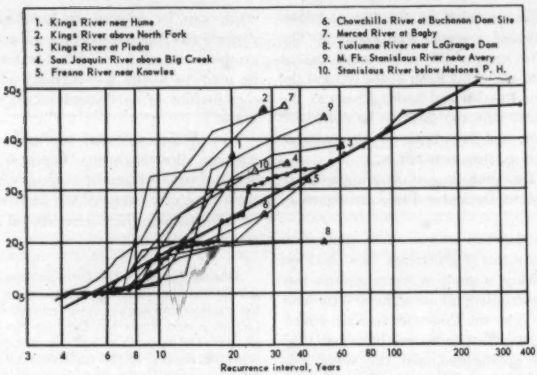
1. Kings River near Hume
2. Kings River above North Fork
3. Kings River at Piedra
4. San Joaquin River above Big Creek
5. Fresno River near Knowles
6. Chowchilla River at Buchanan Dam Site
7. Merced River at Bagby
8. Tuolumne River near LaGrange Dam
9. M. Fk. Stanislaus River near Avery
10. Stanislaus River below Melones P. H.
$5Q_5$
$4Q_5$
$3Q_5$
$2Q_5$
Q_5
3 4 6 8 10 20 30 40 60 80 100 200 300 400
Recurrence interval, Years

Fig. 5 – Synthesis of flood-peak frequency in 10 river stations in Sierra Nevada mountains, 1895–1956

F is another graph with convincing linearity, plotting consistently below the master graph. K is typical of many actual records which have a puzzling upturn at the end, raising the question of whether the historical flood should be used in design.

The other 16 curves are strikingly reminiscent of the graphs we use every day in estimating design discharges. As a group they show that a 50-yr record has a 50–50 chance of fixing the ten-year flood within ten per cent, and a five-year flood within five per cent. If the dog-leg break should be at 3.34 yr, it may appear to be anywhere between two and seven years. The method is general, Figure 3 being a similar analysis plotted by the formula $F = Y/M$.

This hypothetical case to illustrate the scatter of random records of the same phenomenon suggests a practical visual test for homogeneity. After synthesizing the records of a group of stations into one frequency graph, resolve the synthetic graph into a set of chance distributions and compare their mass plotting with a mass plotting of the actual records. If the scatter of the actual records is not materially greater than the chance distribution, the stations may be treated as homogeneous. Otherwise the comparison should indicate which stations should be discarded from the group.

Application in northwestern California—Figure 4 illustrates application of the method to 12 stations in the northwestern part of California on the Eel, Klamath, Russian, Salmon, Scott, Smith, Trinity and Van Duzen Rivers. Records ranged in length from 15 to 45 years, aggregating 314. Basin areas ranged from 214 to 12,100 sq mi.

All records ended with the great flood of December 1955, introducing some upward bias. This was partly offset by plotting to the formula $F = Y/(M - 1/2)$, and partly by giving little weight to the magnitudes of these floods in determining the five-year flood for the base.

The fine lines connect the plotting points of the 12 actual records reduced to the non-dimensional ratio to the five-year flood. The vagrant black line shows and connects these same plotting points after collection in a synthetic record (see Table 1). The straight black line is the resultant graph, fitted visually to the data from the five-year point to the 40-yr point, beyond which the graph appeared biased by the last flood.

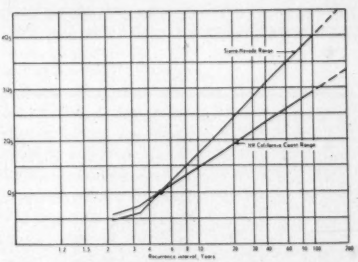

Fig. 6 – Comparison of frequency functions for Sierra Nevada and northwestern California streams

This line was extended for the test of homogeneity, developing a scatter like Figure 2. The scatter indicated acceptability of the group, except possibly for the wild Scott River at the top and the relatively tame Russian and Smith Rivers at the bottom. Records were too short to be conclusive on these streams and there being no other suitable grouping for them, they were left in.

Results of this analysis, including appraisal of the great flood of December 1955, are shown in Table 2.

Application to Sierra streams—One application is not a sufficient test of generality. As a check on wider applicability, a group of Sierra streams was analyzed, first including all unregulated records of major streams from the Cosumnes to Kern River. The test of homogeneity indicated that the central part could be synthesized, and the study was completed with ten stations aggregating 375 yr of record on the Chowchilla, Fresno, Kings, Merced, San Joaquin, Stanislaus, and Tuolumne Rivers.

Figure 5 shows the result of this synthesis, which used the different plotting formula $F = Y/M$. Periods of the separate records ranged from 20 to 61 yr and basin areas from 132 to 1694 sq mi. The synthetic graph was not as well defined as that for the first group, but the all-over trend did not depart much from the plotting position, in spite of the fact that seven of the ten stations had two peaks plotting far above others.

Summary—It is concluded that in extrapolation of frequency graphs for peak discharges large errors can be reduced by combination of nondimensional flood ratios of several streams into one synthetic record. A visual test of homogeneity can be used to assure homogeneity of the selected combination or to discard incompatible components.

Two examples showed application in distinctly different climatic regions. Figure 6 compares the slopes of the two derived frequency graphs. Use of these slopes in extrapolating short records should be more reliable than conventional operations on individual records.

Acknowledgments—The three authors collaborated in development of the synthetic procedure, Long selecting the stations and analyzing the records in northwestern California and Royce the same for the Sierra streams, all as part of research on basic hydrology in the Bridge Research Section of the California Division of Highways.

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Problems of Predicting Sediment Yields from Watersheds

L. C. GOTTSCHALK

Abstract—Three methods in general use for predicting sediment yields from watersheds are: (1) direct sediment-load measurements, (2) estimating yield on the basis of measurements in nearby watersheds, and (3) estimating the rate of erosion in a watershed and the delivery rate of sediment. The third method is a relatively new approach to determination of sediment yield. The objective of the Symposium on Watershed Erosion and Sediment Yields is to assemble existing information and knowledge on sediment yields as a guide to technicians engaged in research and field studies for solution of erosion and sedimentation problems.

The need for information on watershed erosion and sediment yields has grown rapidly during the past two decades, along with the acceleration of Federal, State, and local programs for the conservation, development, and beneficial use of our natural soil and water resources. Such programs normally involve structural works of improvement such as reservoirs for irrigation, water supply, flood control, water power, and other uses; channels for navigation, irrigation and drainage; floodways; and harbor developments.

Proper prediction of the sediment yields from watersheds is a necessity if adequate provision is to be made in the design to offset the effects of sedimentation during the life of such works of improvement. Overestimating the sediment yield results in overdesign and adds unnecessarily to the cost of the structure. Underestimating the sediment yield leads to premature decline in the usefulness of the structure and the services dependent upon it.

The technician predicting sediment yields must draw conclusions and prepare recommendations based on the available basic data and his knowledge of the fundamental principles of sedimentation. The degree of accuracy of his results depends upon the adequacy of available data; his knowledge and understanding of the processes of erosion, entrainment, transportation, and deposition of sediment, and his ability to predict changes which may occur in the watershed to alter the sediment yield during the estimated life of the structure.

The technician must determine whether the basic data he has available are representative of conditions which will prevail during the life of the structure. He must make the necessary adjustments to obtain a realistic estimate. If the basic information he is using was obtained from a watershed unlike that for which he is predicting he must be able to make adjustments for differences in rainfall, runoff, geology, soils, topography, cover, and other conditions which influence erosion, movement, and deposition of sediment. Furthermore, he must consider the method used to measure sediment yield. If sediment-yield data were obtained through measurement of sediment accumulation in reservoirs he must make adjustments for trap efficiency of the structure in order to obtain probable total yield. If suspended load measurements represent the basis of yield data, he must estimate the unmeasured bed load portion to obtain probable total sediment yield.

One of the problems associated with estimating sediment yields involves the forecasting of the long-term effects of application of conservation measures on watersheds. As of July 1, 1956 1,644,000 farmers and ranchers operating 487,335,000 acres of land in the United States were cooperating with soil conservation districts and active in installing conservation measures on their land. During the past five years, over 600 watershed associations were formed in this country to accelerate effective planning and coordinated application of land treatment and structural measures on watersheds. Through the efforts of many groups working on both private and public lands, soil and water conservation measures are being established to reduce erosion, floodwater, and sedimentation damages.

Where the principal sediment load of streams is derived from erosion of the land surface in a watershed, it follows that reduction in land erosion will result in reduction of sediment loads of streams. This is particularly important in small watersheds where incentive for installation of measures is high and application is progressing at a rapid rate. To design, then, on the basis of past or prevailing rates of sediment yield, incurs an unnecessary expense in the structure.

There are three methods generally in use today to predict the sediment yield at a structure site. These are: (1) direct sediment-load measurements at the proposed site; (2) estimating sediment yield on the basis of sediment-load measurements and measurements of sediment accumulations in reservoirs in nearby watersheds; and (3) estimating the rate of erosion in the watershed and the delivery rate of sediment to the structure site.

Direct long-term sediment-load measurements are generally used at proposed sites on the larger watersheds to predict sediment yields. In these instances, it is precluded that the extent of application o' land treatment measures to be installed in the watershed during the life of the structure will not have a measurable effect on the sediment yield. The usual procedure is to plot a sediment-rating curve showing the relationship between discharge and sediment concentration. Long-term sediment yield is then computed by means of this curve and the probable long-term flow-duration curve. Good results are obtained if a sufficient number of measurements have been made to cover all of the ranges of discharge to be expected in the long-term record. Because of the vagaries of nature, representative measurements of all ranges of discharge might be encountered in a short period of only one or two years of record, or measurements may be required for as many as ten years before suitable ranges of discharge are encountered to produce an adequate sediment-rating curve. One of the problems associated with this method is the lack of time usually available between the planning and inception stage of project and the final design stage to make representative measurements.

The relationship between discharge and sediment concentration may vary considerably at a given station, depending upon the grain-size distribution of sediment in transit. Bed load moves as a function of discharge and other hydraulic characteristics of the flow. Where a major part of the load is composed of material which is derived from channel erosion and which moves as bed load, a good relationship may be obtained between sediment concentration and discharge. The concentration of the suspended load which is derived from surface erosion, is more directly related to supply than discharge. Such factors as the nature and location of rainfall in the watershed, the seasonal cover conditions, and other factors have a greater influence on concentration of suspended sediment than does the discharge. Where the bulk of the load is derived from upland erosion, wide variations in sediment concentration may be found in a given discharge.

Direct sediment-load measurements at a site do not provide information in respect to the relative sources of sediment in the watershed. This information is needed to formulate economical and effective land treatment and structural programs for the reduction of sediment yield. Moreover, such information is needed to evaluate the effects of proposed land treatment measures on sediment yields.

When sediment-load measurements cannot be made at a site prior to the design of a structure, the probable sediment yield is sometimes estimated on the basis of measurements obtained in the general region of the watershed in question. Both sediment-load records and records of sediment accumulations in reservoirs are used for this purpose. The method used generally consists of plotting the rate of sediment production per unit of drainage area against the size of drainage area of measured watersheds. An average trend line, or so-called design curve, is drawn and the rate selected on the basis of the size of the drainage area in question.

Size of drainage area is only one of a number of variables which influence sediment yield. Such factors as rainfall characteristics, topography, geology, soils, and cover, have a profound influence on sediment yield from a watershed. The lack of basic data normally requires the use of data from widely scattered, dissimilar, watersheds. This results in a scattering of plotted points when sediment production is plotted against size of drainage area alone. The development of such curves have shown that the average rate of sediment production decreases as the size of drainage area increases. Also, the smaller the watershed, the greater the variation between rates. The selection of a rate based only on size of drainage area, as used in this method, could result in serious error in respect to a proposed structure, particularly for a small watershed. The method is used mostly to obtain rough estimates in the planning stages of projects and is generally recognized as being inadequate for final design.

During the past two decades, a large number of small reservoirs were built in this country for domestic water supply, irrigation, recreation, and flood prevention purposes. Many of these structures are located in watersheds of less than ten square miles in area. The problems of sediment design are particularly difficult because of the

wide extremes of sediment yields encountered for small watersheds. Extensive land-use changes and installation of conservation measures on such watersheds can materially change the sediment yield in a matter of a few years.

Small watersheds are inherently difficult to sample, particularly where such watersheds are remote from observers and the runoff is of a flashy nature. Also, the elapsed time between planning and final design of a small structure is usually much too short to obtain adequate sediment-load measurements at the site. Moreover, runoff records for long periods needed to develop long-term flow duration curves are a rarity. These conditions, plus the fact that sediment-rating curves in themselves, are of little value in forecasting future sediment yields influenced by land-use changes, led to the search for a new method of estimating sediment yields. The method developed involves estimating the amount of gross erosion in the watershed on the basis of physical and climatic conditions and estimating the delivery rate of eroded material to the proposed site.

In the application of this method, normally two types of erosion are recognized: sheet erosion and channel erosion. Sheet erosion is erosion by raindrop impact and transportation of eroded material is mainly by sheet or shallow flow over the surface. Since the transporting capacity of such flow is low, only the finer fractions of the soil—silts, clays, and colloids—are moved any considerable distance. The delivery rate of material eroded in this fashion is low, since much of the eroded material drops out at the breaks in slopes to form what is known as colluvial deposits. The sediment which does get into the channel system constitutes the bulk of the suspended or so-called 'wash load.' Once this sediment is delivered to the stream system, it is easily transported as suspended load by concentrated flow, usually being well distributed throughout the cross section of flow. The flow becomes the transporting medium and the concentration is a function of supply rather than a function of discharge.

Channel erosion comprises mainly gully erosion, streambank erosion, and channel degradation. This type of erosion occurs as a result of the forces exerted by concentrated flow. Material derived from channel erosion is normally thrown directly into the channel system and the delivery rate, at least for the finer fractions, is relatively high. Channel erosion is the primary source of bed material in the stream.

The classification of erosion according to sheet and channel erosion has an added convenience in measuring and estimating erosion in the field. Channel erosion, though limited in area, is readily apparent in depth, and it remains but to measure channel voids in the field and establish the age, to determine the rate of channel erosion. Conversely, sheet erosion is imperceptible in depth but widespread in area and does not lend itself readily to direct field measurement. This type of erosion is estimated on the basis of soil characteristics, cover, degree and length of slope, and rainfall characteristics, drawing upon the results of thousands of plot measurements to establish the empirical relationship between causal factors and rate of soil loss.

On the basis of field measurements of channel erosion, and estimation of sheet erosion, an estimated gross erosion in the watershed is computed. The amount of eroded material delivered to a structural site (sediment yield) depends upon such factors as the watershed area, watershed topography, degree of channelization, and runoff characteristics. Various independent investigators have found significant correlations between delivery rate and such parameters as the size of drainage area, the degree of channelization in the watershed, and the relief ratio (ratio between the maximum and minimum elevations in the watershed and the distance from the top of the watershed to the point of measurement), and several methods are in use today for estimating the delivery rate of eroded material to a site.

Field checks made by comparing the estimated gross erosion in a watershed and the estimated delivery rate to a site with the measured accumulations of sediment in a reservoir has shown very good correlations. Although additional research and field tests are necessary to refine the method further, sufficient progress has been made to date to demonstrate that the approach is sound. It is particularly well adapted to small watersheds where land use changes may greatly influence sediment yields and where other methods of prediction are either physically or economically inept or fail to produce the desired degree of accuracy. The method has additional advantages in providing a means of pin-pointing the relative sources of sediment in the watershed needed in formulating economic and effective land treatment and structrual measures for reduction in sediment damages and evaluating the effects of such measures in project development.

Although relatively new, considerable advancement has been made in developing and refining this method of estimating sediment yields in the past few years. Because of the complexity of the erosion and transportation processes, a number of variables are involved and most investigators have resorted to statistical methods for analyzing data. Generally, the variables used for these analyses are factors which can be readily measured from maps and aerial photographs or computed from existing data and records.

Although good progress has been made to date, there is still room for improvement. For example, better methods are needed for expressing quantitatively the inherent erodibility of soil. This expression might be based on certain measurable physical or chemical qualities of the soil or its infiltration rate, or perhaps it may be necessary to develop mechanical equipment for direct measurement of erodibility in the field. Further refinement is also needed to develop a better relationship between erosion and the intensity, duration, and frequency of rainfall.

A science such as this does not develop answers overnight but must await the results of research in related fields and the collection and analysis of more basic data to develop and better define the various relationships of causal factors to erosion and sediment yields. We have reached the stage of development, however, where the existing information and knowledge should be assembled and published in convenient form as a guide to technicians carrying out watershed studies and to point up the need for additional research for the solution of problems related to watershed erosion and sediment yields. This is the objective of the Symposium on Watershed Erosion and Sediment Yields.

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Factors Affecting Sheet and Rill Erosion

DWIGHT D. SMITH AND WALTER H. WISCHMEIER

Abstract—This paper discusses the two principal processes by which sheet erosion occurs and the six factors which effect the magnitude of the losses. The processes are raindrop impact and transportation of soil particles by flowing water. The factors are length and per cent slope, cropping, soil, management and rainfall. The relative effectiveness of each of the three main conservation practices in control of erosion, contour farming, strip cropping, and terracing is presented. The factors and practices are combined in a rational erosion equation for calculating field soil loss for use in application of conservation practices and in assessing land program benefits.

Sheet erosion has been defined [*Baur*, 1952] as "removal of a fairly uniform layer of soil or material from the land surface by the action of rainfall and runoff." Detachment of soil particles by rainfall impact and splash is probably the only process by which a fairly uniform layer of soil is removed from field surfaces. But soil loss in splash from a specific area occurs only when a directional unbalance occurs as on sloping land, with high winds, etc. When runoff enters the picture transportation of detached particles of soil begins and soon reaches a magnitude resulting in channel flow. This marks the transition from sheet to rill erosion, the type of erosion defined [Baur, 1952] as "removal of soil by running water with formation of shallow channels that can be smoothed out completely by cultivation." This differentiation in erosion types is more easily made on paper than on the land. Plot measurements with which this paper is concerned, is the net result of both sheet and rill erosion.

The erosion processes—The water-erosion processes—detachment by rainfall impact and transportation by flowing water—are very complex. There are a large number of variables which combine to give results in some cases in direct opposition to generally accepted theories or popular belief. There are numerous controversial theories which probably result more from localized viewpoints than from erroneous thinking. The complexity of the problem has necessitated use of empirical methods by conservationists for solution of their field problems.

Cook [1936] listed and discussed the two processes of rainfall erosion: (a) that of falling drops striking the land surface, and (b) surface flow or runoff in which soil is moved from an area of land. *Laws* [1940, 1941] began study of effects of rainfall impact on erosion, which included measuring the fall velocities of water and raindrops and the drop-size distribution in natural rain. *Borst* and *Woodburn* [1942] showed that rainfall impact was the principal cause of erosion from a fallow plot. *Ellison* [1947, seven papers] began his work on raindrop splash in 1936 and subsequently developed theories on detachment and transportation. This approach to the erosion problem was further developed by him and other research workers including *Ekern* [1950, 1953] and *Osborn* [1953, 1954]. This work was in general confined to measurements from small splash cans and from plots 12 × 18 inches in size.

Kinetic energy of rainfall—Rainfall records for the ten-year period 1931–1940 at Bethany, Missouri [*Smith* and others, 1945] have been separated into average annual amounts for different intensity intervals. The amount for each interval decreases rapidly with increases in intensity (Table 1). The kinetic energy was computed for each interval (Table 1) by use of an equation (to be published in a future paper) developed by the authors from published data on drop velocity by *Laws* and *Parsons* [1941] and by *Gunn* and *Kinzer* [1949], and drop-size distribution by *Laws* and *Parsons* [1943]. Annual kinetic energy computed by this method averaged about 12 pct less than by using averages of median drop sizes determined by several investigations [*Ekern*, 1953].

Both the amounts of rain and the kinetic energy of rainfall equal to or greater than specified intensities were plotted against rain intensity in Figure 1. The Bethany control plot study shows average annual runoff for continuous corn to be 8.0 inches and for a rotation of corn-wheat-meadow 4.9 inches. For these amounts, the rainfall curve of Figure 1 shows an average infiltration-rate index of two inches per hour for the rotation in contrast to one inch per hour for continuous corn. The energy in rainfall during runoff was 5200 foot tons per year for the rotation in contrast to 8300 foot

TABLE 1 – *Average annual kinetic energy content of rainfall by intensity groups for the ten-year period 1931–40, Bethany, Missouri*

Intensity-interval group	Amount of rain		Kinetic energy of rainfall	
	At group intensity	At intensities ≥ group	Within group	At intensities ≥ group
inches/hr	inch	inch	ft ton	ft ton
0– 0.24	16.00	29.49	9,770	22,632
0.25– 0.49	2.56	13.49	1,979	12,862
0.50– 0.74	1.63	10.93	1,383	10,883
0.75– 0.99	1.30	9.30	1,168	9,500
1.00– 1.49	1.88	8.00	1,785	8,332
1.50– 1.99	1.31	6.12	1,305	6,547
2.00– 2.99	1.90	4.81	1,990	5,242
3.00– 3.99	1.70	2.91	1,858	3,252
4.00– 4.99	0.73	1.21	831	1,394
5.00– 5.99	0.25	0.48	290	563
6.00– 6.99	0.14	0.23	166	273
7.00– 7.99	0.02	0.09	16	107
8.00– 8.99	0.02	0.07	34	91
9.00–10.99	0.05	0.05	57	57
Total.....	29.49		22,632	

tons for continuous corn. With the rotation, only 23 pct of the total annual energy in the rain was applied when runoff was available for movement of the detached soil from the plots. The rotation provided a good measure of cover for the plot 75 pct of the time. With continuous corn (stalks removed in the fall and no fertility treatment) a fair measure of cover was available only 25 pct of the time. This all helps explain why soil loss under continuous corn averaged 5½ times that with the rotation.

Ellison [1947, pp. 245–248] has shown the equation for relative soil detachment as $E = K\,V^{4.33}\,d^{1.07}\,I^{0.65}$ in which E is relative amounts of soil splashed, during a 30-minute period, K is a constant of the soil, V the drop velocity in ft/sec, d the drop diameter in mm, and I the intensity in in/hr. If drop velocity, equivalent drop size and intensity values from the rainfall energy equation previously mentioned are substituted in Ellison's equation, it is shown that relative soil detachment is 7.2 times as much for an intensity of six inches per hour as for one inch per hour. These data, however, were secured with equal time periods for each intensity. If the assumption is made that total detachment for each rain intensity is directly proportional to time of rain, the increase in relative detachments for equal amounts of rain (1 inch) are much less spectacular as is shown in Table 2.

Potential energy of runoff—Most writers have shown a large contrast between energy of rainfall

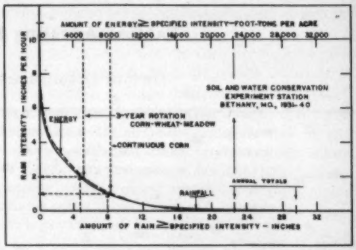

FIG. 1 – Amount and kinetic energy of average annual rainfall equal to or greater than specified rain intensity for ten-year period, 1931–40, Bethany, Missouri, and infiltration rate indices for continuous corn (one inch per hour) and for a three-year rotation (two inches per hour)

and that of runoff. This has resulted from using estimates of kinetic energy of the flowing water as it left the experimental area. The potential energy of runoff is relatively high. For the Shelby soil area with eight per cent average slope 300 ft long, the potential energy of the five-inch average annual runoff is 6800 foot-tons and for the Mexico soil with three per cent average slope 450 ft long, the potential energy of the nine inches average annual runoff is 6900 foot-tons. These figures are about equal to the kinetic energy of the rainfall that occurred during runoff at Bethany although only 30 pct of the total. A large portion of this potential energy of runoff is used in overcoming friction of flow or in work on the surface as runoff passes down the slope. Also, a significant part of the kinetic energy of the rain is transmitted to the runoff water as the raindrops strike the flowing sheet of water and add to its turbulance.

Other factors affecting soil loss—The principal factors in addition to rainfall which are generally considered as affecting the magnitude of soil loss are as follows: (a) per cent slope, (b) length of

TABLE 2 – *Effect of rain intensity on relative detachment, calculated by use of Ellison's equation*

Rain intensity	Relative detachment	
	Per 30-minute period	Per inch of rain
in/hr		
1	1.00	1.00
2	2.18	1.09
4	4.71	1.18
6	7.16	1.20

slope, (c) cover or cropping system, (d) soil, and (e) management.

Per cent slope—The first comprehensive study of the effect of slope on soil loss was published by *Zingg* [1940]. He concluded that soil loss varies as the 1.4 power of the per cent slope. His study was based on data by Duley and Hays working in Kansas, Diseker and Yoder in Alabama, and a series of rainfall simulator studies which he performed at Bethany, Missouri.

The exponential equation, as an empirical description of the slope soil-loss relationship, is quite satisfactory under most field conditions. However, it indicates zero soil loss for a zero per cent slope, a condition which does not exist in the field unless the field is completely diked to prevent runoff. For the extremely steep slopes of soils that are easy to detach and transport, a decrease in rate of increase of soil loss as runoff reaches its capacity to transport soil appears possible. These slopes, however, are seldom in cultivation.

For better description of the relationship on the flatter slopes of Midwest claypan soils, *Smith* and *Whitt* [1947] proposed the following equation, the constants of which were evaluated by use of *Neal's* [1938] rainfall simulator data for Putnam soil

$$R = 0.10 + 0.21\ S^{4/3}$$

in which R is relative soil loss in relation to unity loss for a slope of three per cent. S is per cent of slope.

Seventeen years of data from each of two locations are now available for evaluation of the per cent slope-soil-loss relationship. Data by Hays at the Upper Mississippi Valley Conservation Experiment Station, LaCrosse, Wisconsin, covers four slope groups from 3 to 18 pct on Fayette soil. The plots were cropped to continuous barley for the first five years and to corn-oats-meadow rotation for the succeeding 12 years. Data by Lillard and others working at Blacksburg, Virginia covers 17 years of corn-wheat-meadow rotation on five slope groups ranging from 5 to 25 pct. Similar data comparing only two slopes are available from studies in several other states.

The parabola appears to meet satisfactorily the requirements for an empirical equation to express the relationship between per cent slope and soil loss throughout the full slope range as experienced on cropped fields. It estimates a small soil loss from a zero per cent slope, and the constants in the equation for different soil types can be evaluated readily from data by the method of least squares.

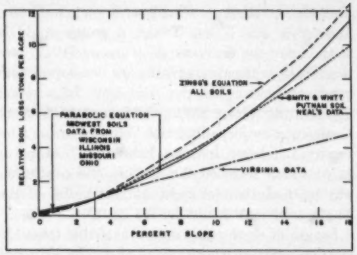
RELATIVE SOIL LOSS—TONS PER ACRE
PERCENT SLOPE
ZINGG'S EQUATION ALL SOILS
SMITH & WHITT PUTNAM SOIL NEAL'S DATA
PARABOLIC EQUATION MIDWEST SOILS DATA FROM WISCONSIN ILLINOIS MISSOURI OHIO
VIRGINIA DATA

FIG. 2 – The relationship of per cent slope and soil loss as described by parabolic equations derived from presently available data and by other type equations previously published; all equations adjusted to give unity soil loss on a three per cent slope

The constants of the parabolic equation fitted to Hays' data and one fitted to Zingg's rainfall simulator data when adjusted for similar cropping conditions are nearly identical. Data from studies at Dixon Springs, Illinois, and Zanesville, Ohio, comparing two slopes at each location, when adjusted in magnitude to conform with conditions at LaCrosse, also fit the slope of the parabola fitted to the Wisconsin data. The combined data for the four studies give a very good least-squares fit to the equation

$$A = 0.43 + 0.30\ S + 0.043\ S^2$$

in which A is soil loss in tons per acre.

The Virginia data, however, shows a nearly linear relationship. The parabolic equation fitted to these data is

$$A = 0.24 + 0.55\ S - 0.004\ S^2$$

A comparison of the equations for per cent slope-soil-loss relationship is shown in Figure 2 with published equations by Zingg and by Smith and Whitt.

Runoff in Hays' and Zingg's studies increased significantly with increase in per cent slope, although the two soils were quite different. In the Virginia study, it remained nearly constant across the entire range of slopes.

Length of slope—In his study of the effect of slope length on soil loss, Zingg concluded that total soil loss varied as the 1.6 power of the length, and soil loss per unit area as the 0.6 power of the length. He used data from Bethany, Missouri;

Guthrie, Oklahoma; Clarinda, Iowa; LaCrosse, Wisconsin; and Tyler, Texas. A group study in 1945 under the direction of *Musgrave* [1947] proposed 0.35 as the average value for the slope length exponent for soil loss per unit area. In a recent group study (Joint SWC, ARS, and SCS Work Conference on Slope-Practice Values, Purdue University, Lafayette, Indiana, February 27–March 1, 1956) which included the authors, the conclusion was reached that for field use the value of the length exponent should be 0.5 ± 0.1.

Length of slope data are now available from 136 location-years at ten locations where the principal crops were either corn or cotton. The average value of the length exponents by locations weighted for years is 0.46. There is a wide variation in location-year values of the length exponent. In some instances it is negative. Average values for the different locations varied from 0 to 0.9. An explanation of the variations was not readily discernible. Magnitude of the exponent appears to be related both to soil and cover, but more positively to runoff. The larger exponents are, in general, associated with location data which show an increase in runoff with increased slope length and the smaller with locations where the reverse occurs. The largest values are from Bethany, Missouri, and Guthrie, Oklahoma, and the zero or no significant difference from Temple, Texas. It is logical to expect little change in soil loss with increase in slope length when runoff has a limited transport capacity due to a decreasing volume or decreasing turbulance, and is quickly saturated as it passes down a slope of easily detachable soil.

Soil loss is generally expressed in tons per acre. Since the rate of soil loss increases on most soils with an increase in slope length, the loss on the lower segments of slope will be appreciably greater than the average for the entire length. This can be illustrated by computing the relative soil loss for segments of an average slope length assuming the increase in average soil loss per unit area is proportional to $L^{0.5}$. Computed values for four segments of a 300-foot slope length are

Length segment foot	Relative soil loss per unit area ton
0–75	1.00
75–150	1.83
150–225	2.37
225–300	2.80
Average for 0–300	2.00

The relationship of length of slope to soil loss has been controversial. This is partly the result of the large variation in experimental results which have not been satisfactorily explained. Another reason has been the different interpretations of what constitutes length of slope. For this reason the following definition of slope length was prepared by the recent slope-practice conference group.

Slope length is the distance from the point of origin of overland flow to either of the following, whichever is limiting for the major portion of the area under consideration: (1) the point where the slope decreases to the extent that deposition begins, or (2) the point where runoff water enters a well-defined channel. A channel is defined as a part of a drainage network of a size that is not readily obliterated by cultivation and usually suitable for stabilization with grass. It may be a constructed channel such as a terrace or diversion.

Cover—Cover as a variable in erosion control has generally been studied on small runoff plots 70 to 90 ft long and 6 to 14 ft wide. Such plots were established on the ten original soil erosion

TABLE 3 – *Runoff and soil loss from plot studies in Missouri on Shelby loam, 1930–41, and on Mexico silt loam, 1941–50*

Cropping system	Plot data	Annual rainfall	Annual runoff	Annual soil loss
		inch	inch	tons/ac
Continuous Corn[c]	[a]	29.49	8.20	50.93
Corn-Wheat-Meadow[c]	[a]	29.49	4.90	9.06
Bluegrass[c]	[a]	29.49	2.44	0.16
Corn-Oats[c]	[b]	39.16	11.74	6.08
Corn-Corn-Oats-Wheat & Sw. Cl.	[b]	39.16	8.83	4.03
Corn-Oats & Sw. Cl. (catch)	[b]	39.16	8.42	3.07
Corn-Wheat-Sw. Cl. (Hay)	[b]	39.16	7.89	2.02
Corn-Wheat-Meadow	[b]	39.16	8.42	1.67
Corn-Wheat-Meadow-Meadow	[b]	39.16	8.39	1.13
Wheat & Lesp. (Pasture)[d]	[b]	39.16	9.20	2.20
Tim., Bl. Gr., Sw. C., & Lesp. (Pasture)[d]	[b]	39.16	6.83	0.26

[a] Plots 6 × 72.6 feet on eight per cent slope; Shelby loam soil.

[b] Plots 10½ × 90 ft., on three per cent slope; Mexico silt loam soil.

[c] No soil treatment; other systems received lime and starter treatments on small grain 1941 through 1946, and full treatment, based on soil tests, 1947 through 1950.

[d] Grazing rate, 1–4 animal units per acre, four to six months per year.

experiment stations by Bennett during the period, 1930–33. They were patterned in general after the earlier work in Missouri by Miller and Duley. An example of the type of data secured from these studies is shown in Table 3, where average annual losses for several rotations are shown. These rotation averages were secured by averaging the annual runoff and soil losses from plots on which all crops of the rotation were grown.

While annual losses under different rotations reflect the effect of different crops or crop sequences they do not show the cause of favorable or unfavorable losses [*Smith*, 1946]. This can be revealed by study of crop-year or preferably crop-period losses. Crop-year losses are those that accumulate during the full calendar year in which a crop is harvested. Crop-period losses, except for meadows with more than one harvest year, are those that accumulate from the beginning of seedbed preparation or harvest of the preceeding crop, to harvest of the crop or beginning of seedbed preparation for the following crop. Crop-period losses obviously represent a more accurate measure of a crop or crop sequence in control of runoff and erosion than do crop year losses. Crop-year losses, however, are more easily tabulated and used for estimating rotation losses for systems not under measurement than are crop period losses. Crop-year soil losses for the different sequences in which crops may be grown have been tabulated by Soil Conservation Service for use by their farm planning technician in limiting field soil loss to a predetermined level. Table 4 shows losses by crops for two rotations of Table 3, tabulated by crop periods and by crop years.

Study of the cover factor on small runoff plots, which represent a small segment of a field area, has been necessary because of the large number of crop and cover combinations that are possible or are in use. Extrapolation of the data has been necessary when applying it to field areas, although relative values for the different cover combinations have been used directly. Erosion measurements from the plots include sheet erosion and some rill erosion, although rill erosion did not develop to the full extent on these short slopes.

Osborn [1954], in studying the effect of density of range cover on erosion, used the rainfall simulator with splash cups and small runoff plots 12 × 18 inches. He showed that a cover of 3500 lb/ac of ordinary crops or grasses and 6000 lb/ac of tall coarse crops and weeds would control 95 pct of rain drop energies. As crop cover decreased below these amounts, rates of soil splash increased very rapidly.

Soils—Soil factors which express the relative erodibility of different soils were developed in 1945 by a group of soil conservation research workers under the direction of *Musgrave* [1947]. Annual losses for continuous corn were adjusted to a common slope of nine per cent and a common 30-minute rainfall amount. Further development was made during the next several years by operations and research workers of the Soil Conservation Service for the mid-western states. Interpolations for soils on which soil losses had not been measured were made by considering the physical properties of the soil after soil technologists had classified the soils by characteristics considered to be related to potential erosion hazards.

TABLE 4 – *Runoff and soil loss tabulated by crop period and by crop year for two rotations of Table 3*

Crop or Cover	Crop Period		Runoff		Soil loss	
	Dates	Rainfall	Crop period	Crop year	Crop period	Crop year
		inch	inch	inch	tons/ac	tons/ac
Corn	Apr. 27–Oct. 8	23.23	5.48	10.89	6.95	7.78
Corn stalks	Oct. 9–Apr. 28	12.48	4.49	...	.95	...
Oats	Apr. 29–July 3	14.15	5.11	12.60	3.18	4.47
Oat stubble	July 4–Apr. 26	28.47	8.40	...	1.08	...
Rotation average		39.16	11.74	11.74	6.08	6.08
Corn	Apr. 27–Oct. 7	23.23	3.58	8.21	3.01	3.65
Wheat	Oct. 8–June 28	26.29	6.45	7.58	2.28	2.05
Sw. Clover (Hay)	June 29–Apr. 26	67.97[a]	13.63	7.87	.78	.37
Rotation average		39.16	7.89	7.89	2.02	2.02

[a] Twenty-two month period.

A more recent attempt at determining soil factors made use of erosion rates under a corn-small grain-meadow rotation from four Soil Conservation Experiment Stations in the midwest. Adjustments were made for differences in slope. Table 5 shows some of these factors. They cannot be considered precise factors, largely because of lack of a satisfactory method of adjusting for rainfall differences.

Osborn [1954] used soil splash cans to determine differences in soil detachability rates. He found a wide range of rates even for the same soil. He reported that detachability rates of medium-textured soils averaged somewhat lower than those of either fine-textured or coarse-textured soils. This technique appears to have excellent possibilities for rating of a large number of soils as to their erosivity.

Management—This factor is a measure of deviation in field application of soil, crop, and conservation practices from standards maintained in operation of the experimental cropping system plots from which runoff and erosion measurements were secured. This includes timeliness of operations, management of crop residues, fertilizer treatments, precision in application of conservation practices, and use of the optimum number of seedbed operations. So far, evaluation has been largely by judgment. It is generally a plus or minus 20 to 30 pct deviation from normal calculated rates.

Practices for reduction of field erosion losses—The three practices for control of sheet and rill erosion other than cover or cropping are contour farming, strip cropping, and terracing. All three are somewhat similar in their actions and operate to control (or limit) both sheet and rill erosion. They are frequently referred to as supporting practices.

Contour farming—This practice relies on a series of contour rows to drain runoff to a waterway. As such, it reduces the steepness of slope over which overland flow passes. But since the capacity of the contour rows to carry runoff is small, the practice breaks down as the storm runoff intensity increases. When this occurs, soil loss approaches, or may even exceed, that for up-and-down-hill farming. The relative value of contouring is expressed as a ratio (decimal) of the up-and-down-hill soil loss. The lowest numerical value of the ratio (highest effectiveness) is for the intermediate slopes. The factor, or ratio, approaches unity for both the flatter and the steeper slopes. As the slope increases, the standard corn row cross-section available for holding runoff decreases and becomes zero at a slope of about 25 pct. Hence, at this point the practice factor value is considered unity. On the extremely flat slopes the up-and-down-hill soil loss approaches that of contouring and becomes equal to it at a zero slope. This too results in a practice factor value of unity. Recommended values for different slope groups are shown in Table 6.

TABLE 5 – *Soil factors calculated and interpolated for several Midwest soils*

Soil	Location	Relative soil loss
Marshall	Clarinda, Ia.	1.00
Mexico	McCredie, Mo.	1.25
Shelby	Bethany, Mo.	1.25
Fayette	LaCrosse, Wisc.	1.25
Baxter	...	1.00
Union	...	1.25
Ida	...	1.50

TABLE 6 – *Recommended conservation practice factors for estimating field soil loss*

	Slope group	P_s (contouring)	P_{ss} (strip cropping)[a]	P_{ts} (terracing & contouring)
	pct			
A	1.1– 2	0.60	0.30	...
B	2.1– 4	0.50	0.25	0.10
C	4.1– 7	0.50	0.25	0.10
D	7.1–12	0.60	0.30	0.12
E	12.1–18	0.80	0.40	0.16
F	18.1+	1.00	0.50	...

[a] A system using a four-year rotation of corn-small grain-meadow-meadow.

Strip cropping—Strip cropping functions by filtering suspended soil from runoff as it passes from a cultivated strip to a sod strip. Plot measurements at LaCrosse, Wisconsin, and Bethany, Missouri, indicate that the soil loss from the strip-cropped field is about 50 pct of that with contouring. Since the sod strip acts as a filter, the measured loss from the field is similar to that from the end of a terrace.

Terracing—This practice breaks a long slope into segments of shorter length. Runoff is intercepted by the channel and conducted across the field at a non-eroding velocity. This results in deposition in the terrace channel of part of the soil transported to the channel. The average ratio of soil loss from contour farmed terraced fields to that from unterraced fields not farmed on the contour is about 0.04. A somewhat larger factor is frequently used. Terrace factors (including contouring) were developed by assuming that (1) terraces would divide the average slope length into

six segments, (2) average soil loss per unit area is proportional to $L^{0.5}$, and (3) contour farming would make the same reduction as when used alone. Factors thus determined are shown in Table 6.

Estimating field soil loss—Smith [1941] published a graphical method for applying the results of plot measurements to field areas by use of Zingg's length and per cent of slope equations. The method was further developed for use in Iowa by *Browning* and others [1947]. Other articles on the subject were published by *Musgrave* [1947] and by *Smith* and *Whitt* [1947, 1948]. They used the method to prepare crop-practice recommendations for Missouri [*Smith, Whitt* and *Miller*, 1948]. All this work was based on use of the following empirical equation for estimating field soil loss.

$$A = C\,S\,L\,K\,P\,M$$

in which

A is average annual field soil loss in tons per acre.

C is average annual plot soil loss in tons per acre for a selected rotation with farming up and down slope (Table 3, Mexico silt loam plot data).

S and L are relative factors for per cent (S) and length (L) of slope adjusted to give unity loss on a three per cent slope 90 ft long, the same as the Mexico silt loam plot data shown in Table 3; see Tables 7 and 8 for factor values.

K is a soil factor taken directly from Table 5 since the soil factor for Mexico silt loam is 1.0. Soil factor values must be relative to a unity value for the soil of the plots from which C values are secured.

P is the factor for conservation practices in relation to a unity value for up-and-down-hill farming; see Table 6 for factor values.

TABLE 7 – *Percent slope-soil loss factors based on the parabolic equation for four Midwest soils and adjusted to a unity value on a three per cent slope*

Slope	Factor	Slope	Factor
pct		pct	
0	0.25	9	3.85
1	0.45	10	4.49
2	0.70	12	5.94
3	1.00	14	7.59
5	1.75	16	9.44
6	2.19	18	11.48
8	3.04	20	13.73

TABLE 8 – *Length of slope-soil loss factors*

Length	Factors			Length	Factors		
	Exponents of L				Exponents of L		
	0.4	0.5	0.6		0.4	0.5	0.6
ft				ft			
72.6	0.9	0.9	0.9	500	2.0	2.4	2.8
90	1.0	1.0	1.0	600	2.1	2.6	3.1
100	1.0	1.1	1.1	700	2.3	2.8	3.4
200	1.4	1.5	1.6	800	2.4	3.0	3.7
300	1.6	1.8	2.1	900	2.5	3.2	4.0
400	1.8	2.1	2.5	1000	2.6	3.3	4.2

M is the management factor, with management of the crop rotation plots considered unity.

With this equation and a limited amount of field data, the conservationist can select the cropping system and conservation practice necessary to limit field loss to a specific figure. The equation can also be used to estimate rates of erosion before and after application of a land program to determine effectiveness of control and to place a monetary value on benefits. It must be recognized that the method is empirical, and as such it is subject to the limitations of empirical relationships. It is the best approach now available for the uses listed above. With added research and use, its accuracy can be improved.

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Fluvial Sediment Transportation

PAUL C. BENEDICT

Abstract—The modes of sediment transport, several related flow parameters and the problem of total load determinations are briefly discussed. The need for additional field and laboratory research to define all factors that affect the sediment discharge of streams is emphasized.

Most investigations of sediment movement have been largely devoted to the three so-called modes of transport: contact, saltation, and suspended. These modes of transport usually have been studied individually rather than as indivisible parts of the total sediment movement. Because in reality there is no sharp dividing line between the three modes of transport, the individual approach has not been too successful for determining the total load of streams flowing in channels that are easily eroded or channels that are stable except during high flows.

Modes of transport—In contact-load or, in a restrictive sense, bed-load transport, particles may move in substantially continuous contact with the stream bed. The particles are dragged along, as it were, by the tractive force of a vertical prism of water moving downstream. In saltation, sediment particles progress by a bouncing action. The particles that are lifted from the bottom acquire kinetic energy; when they descend to the bed, they may bounce, knock other particles off the bed, or both. *Kalinske* [1942] has concluded that, in a stream, particles bounce only a few grain diameters into the flow; therefore, sediment movement by saltation is relatively insignificant. In suspended-sediment transport, the settling of particles by gravity is balanced by the net upward transfer of particles by vertical components of turbulence. In other words, the transport of sediment particles from a source of high concentration to a zone of lesser concentration by an upward transfer of a mass of water would exceed the transport of particles in the reverse direction by the downward transfer of an equivalent mass of water were it not for the settling of particles by gravity.

Lane [1944] has described an intermediate type of transport that he calls 'ripple-wake suspension.' Bed-material particles are lifted from a point of ripple in a large-scale upward-moving turbulent current. The turbulent current moves to the surface to form a 'boil,' and carries sediment particles, which disperse and settle to the bottom over a considerable area downstream. Lane observed that for streams carrying mostly stream-bed material the concentration of sediment particles in the turbulent current was many times higher than that in the stream a few feet on either side. *Matthes* [1947] applied the term 'kolk' to this type of macroturbulence. The kolks that he describes occur not only in sand-bed streams but in boulder-strewn streams. In streams having course beds, the lifting force of a kolk entrains gravel and cobblestones and is important in bedscour and pot-hole formation. Matthes observed that macroturbulence was less active as the sediment load increased.

Another characteristic of sediment movement, particularly for those sizes of particles composing the bed of the stream, is that sediment particles do not move continuously. *Friedkin* [1945], by laboratory studies of meander progression, showed that particles eroded from a cutbank usually move to the first or second point bar downstream. *Einstein* [1950] and many others have shown that contact-load particles move in steps. Some of the fine particles that are introduced to a stream by storm runoff may also be deposited on a stream bed because of decreases in discharge and turbulence as a flood wave outruns its sediment load [*Heidel*, 1956].

In retrospect, perhaps too much emphasis has been placed on the individual modes of sediment transport and not enough on the mechanics of total transport. In the future, we must, if we are to make satisfactory progress in the study of fluvial sediment, consider the determination of the total sediment discharge of a stream as one of our major objectives.

Vertical distribution of suspended sediment—By the turbulence-suspension theory, the distribution of suspended sediment of one size was presented by *Rouse* [1937] by

$$\frac{c_y}{c_a} = \left[\frac{a}{d-a}\,\frac{d-y}{y}\right]^z$$

That is, the ratio of the sediment concentration at a point y above the bed to that at a distance a varies exponentially with the ratio of depth above

the point $(d - y)$ to the distance below the point (Fig. 1). The exponent z is a symbol representing, in theory, the relationship between V_s, the settling velocity; u_*, the shear velocity; and k, the von Karman universal constant.

$$z = V_s/u_*k \tag{2}$$

These equations are intended for the main body of flow; they do not apply at the water surface, where the computed concentration would be zero, or at the bed, where the computed concentration is infinite.

In natural streams, the distribution of concentration in a vertical usually may be adequately represented by (1) and (2) for relatively fine-size particles. Actual distributions for coarse particles do not follow the equations. *Einstein* and *Chien* [1954] and *Chien* [1956] considered the equations as oversimplifications and proposed solutions, from second approximations of the basic theory, that are more nearly in agreement with field data. The exponent z by these solutions increased much less with increasing particle size than the exponent z computed from (2).

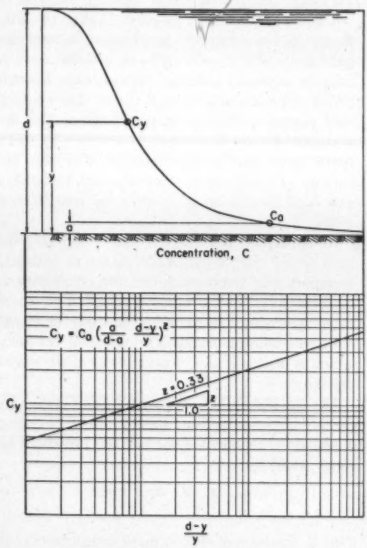

FIG. 1 – Theoretical concentration of unigranular particles in a vertical section

An assumption of the turbulence-suspension theory is that no net transfer of particles takes place across a horizontal reference plane. The theory, therefore, is not quite applicable to small areas in the vicinity of the kolk action described by Matthes or to the 'ripple-wake suspension' observed by Lane. One should, therefore, anticipate a difference between an exponent z computed with the theory and an exponent z_1 determined from suspended-sediment samples, which may include particles that were moving diagonally upward near the source of a kolk and downward at a point farther downstream.

Colby and *Hembree* [1955] found empirically that an exponent for particles (of a size fraction) distributed throughout a cross section varied as the 0.7 power of the settling velocity if the settling velocities computed by *Rubey* [1933] were used. *Hubbell* and *Matejka* [in preparation] found that the exponent varied as the 0.6 power if fall velocities were used.

Settling velocities—The settling velocity V_s applicable to (2) has been of some concern in transport studies. *Einstein* [1950] and *Colby* and *Hembree* [1955] have used Rubey's equation of settling velocity, which is reducible to the form

$$C_D = 2 + 24/R \tag{3}$$

in which C_D is the drag coefficient and R is Reynolds number. The relationship, although deficient in that the computed drag coefficient never is less than two, is generally adequate when used in the Einstein and modified Einstein procedures for computing total load. Another relationship more in accord with data on drag coefficients and Reynolds number could be used for these procedures, with compensating changes principally in z.

Particles falling in mass in a stratified system usually fall faster than particles falling alone; particles falling in a dispersed system usually fall slower than particles falling alone [*Colby*, in preparation]. *Vanoni* [1946] and others have used the settling velocity of particles falling alone for computing z by (2).

Results of several investigations of settling velocity of particles are available, and data frequently are expressed as plots of drag coefficients versus Reynolds number. For a standard of settling velocities, *Colby* and *Christensen* [1956] have proposed the terms 'standard fall velocity' and 'fall diameter.' The standard fall velocity is

the terminal uniform settling velocity of a particle falling alone in quiescent distilled water of infinite extent and at a standard temperature of 24°C. The fall diameter of a particle is the diameter of a sphere that has a specific gravity of 2.65 and has the same standard fall velocity as the particle. Fall diameters are obtained from fall velocities by use of data for quartz spheres by *Rouse* [1939]. Colby and Christensen's expression of results in terms of a fall diameter is perhaps a concession to those accustomed to thinking in terms of a physical size.

Vertical distribution of velocity—The von Karman universal constant is determined usually from the vertical-velocity distributions. It is proportional to the slope of a line on a plot of point velocity versus the logarithm of the height of the point above the stream bed (Fig. 2). For relatively clear water flowing in laboratory flumes or in pipes, the von Karman constant is about 0.4, which is often used when the logarithmic velocity equation is used in studies of sediment transport. For natural channels and for sediment-laden flow, the von Karman constant usually differs from 0.4. *Einstein* and *Chien* [1954, 1955] and *Chien* [1956] consider that energy used in suspending the sediment particles affects the vertical distribution of velocity, and therefore the von Karman constant is reduced. In natural streams, the vertical-velocity distributions may vary considerably across a section; some distributions of velocity for the Middle Loup River at Dunning, Nebraska, when the bed was nearly plane, are shown for March 7, 1956, in Figure 3. The von Karman constants for five verticals ranged from 0.24 to 0.36.

If sand dunes are present, the velocity distribution changes greatly as flow progresses from crest to trough and then again to crest. If the ratio of dune height to depth of flow is large, the measured velocity distributions are only approximately represented by the logarithmic expression for velocity. Some distributions are shown for October 23, 1953, in Figure 3 for a section having an undulating or sand-dune bed. For one vertical (Station 46), the velocity increased downward from the water surface; for the other four verticals, the magnitude of computed k ranged from 0.39 to 2.59. Other investigators also have found k values that greatly exceeded 0.4. It is considered inappropriate to apply the name 'von Karman constant' to a computed k when the dune height-depth ratio is large.

The pattern of turbulence may depend on the vertical-velocity distribution. Because the turbulence pattern affects the suspension of particles, it will affect the exponent z_1. From another viewpoint, the change in k should be compensated by a change in z_1 so that the amount of sediment in suspension remains constant, or nearly so, from trough to crest of dunes. We have no field data of velocity and concentration distributions at successive downstream sections over sand dunes. However, the variation of k with z_1 from data for stations on transverse sections of streams is shown in Figure 4.

Heavy concentrations of particles near the stream bed have been found by *Einstein* and *Chien* [1955] to affect the distribution of velocities.

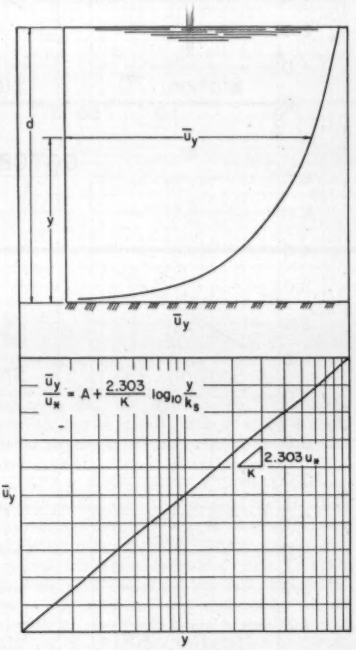

FIG. 2 – Theoretical distribution of velocity in a vertical section

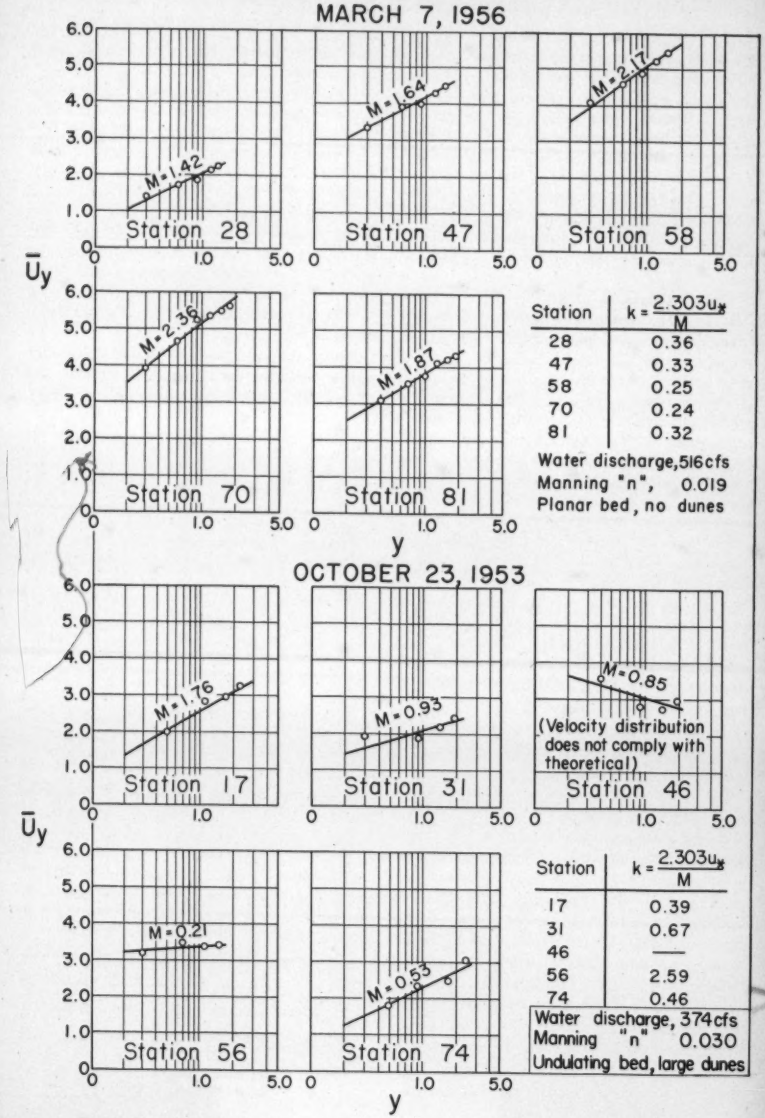

FIG. 3 – Vertical distribution of velocity at Section C_3, Middle Loup River at Dunning, Nebr.

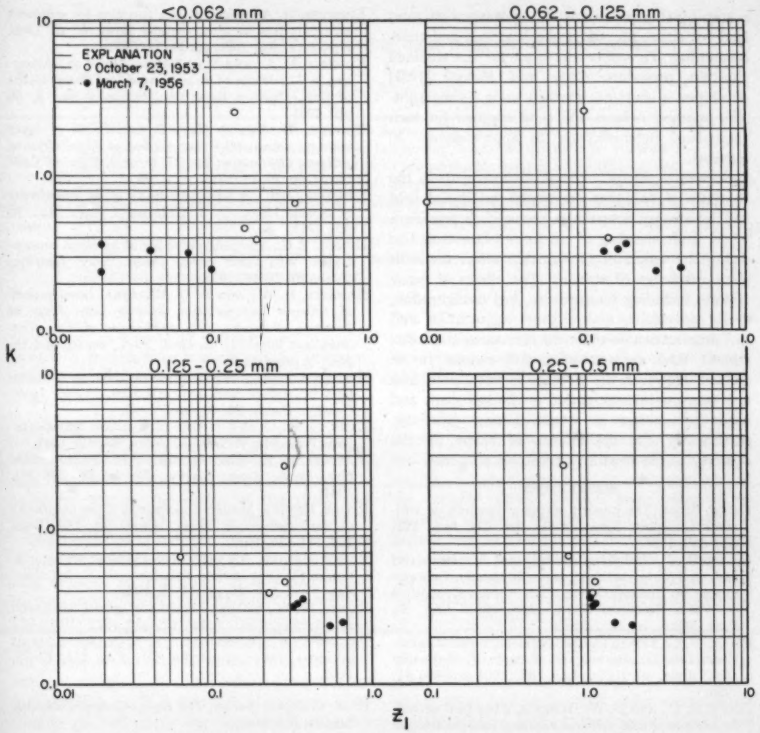

FIG. 4 – Graph of Z_4 versus K, Section C_3, Middle Loup River at Dunning, Nebr.

Points representing the velocities for the main body of flow plotted as straight lines on semilogarithmic charts, but points representing the velocities near the bed plotted as curves. Concentration data, if plotted as log C_y versus log $(d - y)/y$, were similarly curved.

Sediment transport—Movement of sediment as bed load has been studied by many investigators. *Einstein* [1950] recognized, as had most investigators, that particles comprising the bed move partly as contact load and partly as suspended-sediment load. He devised a method by which equations for both types of transport were combined in a formula that described movement of bed material. This was done by assuming that contact load moved in a layer two diameters thick and by assuming that the concentration of sediment particles moving in this bed layer could be used, at the top of the bed layer, as the reference concentration C_a of the suspended-sediment concentration distribution; see Eq. (1). His step-by-step procedure for the determination of the bed-material load of streams is based on measurements consisting of bed-material samples, stream cross sections, and slope of the related reach. To utilize fully the usually available hydraulic data, to improve the reliability and applicability of the method for more streams, and to determine total sediment load instead of bed-material load, *Colby* and *Hembree* [1955] have modified the Einstein procedure on the basis of field research. The modification as outlined by Colby and Hembree is also

a step-by-step procedure. Computations of total load by either procedure are laborious and time-consuming. To reduce the work for the modified Einstein procedure *Colby* and *Hubbell* [1957] developed a short cut method using nomographs. This method reduces the time required for each total load determination to approximately 20 minutes.

Summary—Despite recent advancements in the concepts of sediment movement, additional field and laboratory research is required to provide a better understanding of the known factors and to define the unknown factors that affect the sediment discharge of streams. The effects of many factors, including temperature, bed configuration, dune movement, and channel aggradation and (or) degradation on sediment movement and interrelated flow characteristics still remain to be defined. However, the modified Einstein procedure now permits reinvestigation of channel shape and other parameters of stream-channel geometry, particularly the dependence of shape on the capacity of the stream to transport sediment.

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Importance of Sheet Erosion as a Source of Sediment

Louis M. Glymph, Jr.

Abstract—Estimating sources of sediment comprising the sediment yield from a watershed is recognized as a difficult but important step in planning means and measures for watershed protection and development. The paper refers to procedures for making such estimates and presents the results of studies on 113 watersheds in various parts of the country. Sheet erosion is clearly the dominant source of sediment in most of the watersheds cited and the opinion is advanced that this is generally the case in the more humid parts of the country. In the cases cited, however, the proportion of sediment yield derived from sheet erosion ranged from 11 to 100 pct of the total and the conclusion is reached that watersheds must be considered individually with respect to sources of sediment.

Introduction—In planning erosion control programs and measures for reduction of sediment yield it is necessary to know where the sediment comes from. For the engineer or geologist engaged in such programs, information on sediment source is about as important as information on sediment yield. He must determine the significance, as sources of sediment, of the several types of erosion in a watershed and utilize the information as a basis for guiding the choice of the kinds and amounts of corrective measures required.

Determination of sediment sources is one of the most difficult problems facing the watershed planning engineer. It is relatively much easier to estimate rates of sediment yield than it is to determine the sources of the sediment. Reservoir sedimentation surveys, sampling of streamflow, and some of the sediment transport formulas, are rather clear-cut and straight-forward procedures for determining sediment yields but records of sediment yield usually do not imply the sources of sediment. Determination of sediment sources is the next step in watershed planning after the determination of sediment yield and to some extent becomes the ultimate objective of the planning engineer.

Procedures for estimating erosion rates—Basically, the problem of estimating sediment sources involves: (1) estimating the average annual rate of gross erosion in a watershed, giving expression to sheet erosion, gully erosion, channel erosion and other types of erosion which contribute significantly as a sediment source, and (2) estimates of sediment delivery rates for each significant type of erosion.

In the paper, on sheet and rill erosion, presented as a part of this Symposium, Smith and Wischmeier have outlined the factors which influence the rate of sheet erosion and have presented data of a type derived from research in various parts of the country which enable an estimate of sheet erosion rates from information on soil characteristics, degree of slope, length of slope, rainfall, land use, cropping systems, conservation measures, etc. Further, these authors have made reference to several publications which prescribe procedures and list factors which may be employed in estimating sheet-erosion rates for specific segments of the country. Other workers have extrapolated pertinent research findings, with adjustments in factors such as rainfall, soil characteristics, cropping and farming systems, and have evolved unpublished empirical procedures and relationships for estimating sheet erosion for local conditions and for broad agricultural areas.

Essential research and background data are far from complete but there does seem to be sufficient information to enable estimates of sheet erosion which are at least in the right order of magnitude for the eastern half of the country. With the limited data now available such estimates cannot be made for most of the area west of about the one-hundredth meridian.

Procedures such as those referred to above, where requisite data are available, provide a means for estimating sheet erosion in quantitative terms on a watershed basis.

Empirical or mathematical procedures for estimating the rates of stream channel and gully erosion are not as well defined or authenticated as are those for estimating sheet erosion in the eastern part of the country. By and large, estimates of channel and gully erosion rates have to be evolved some other way.

In some watersheds estimates of rates of gully and stream-bank erosion can be made from comparative study of aerial photographs of different

TABLE 1 – *Examples of sediment sources as derived from watershed surveys*

Location		Size of drainage area	Relative sediment source					Reference[b]
State	County		Sheet	Gully	Stream channel	Valley trenching[a]	Other	
		sq mi	pct	pct	pct	pct	pct	
New York	Erie and Wyoming	437	47	...	53	...	...	(8)
New Jersey	Mercer	47.8	74	15	11	...	...	(8)
Maryland	Harford	1.7	76	4	18	...	2	(8)
Ohio	Fairfield	49.1	79	8	10	3	...	(8)
Ohio	Highland	43.8	71	10	19	...	...	(8)
Illinois	Coles	1.41	42	58	...	...	...	(7)
Illinois	McLean	67.3	86	8	6	...	...	(8)
Illinois	Franklin	4.03	90+	...	...	...	...	(3)
Illinois	Jackson	3.10	90+	...	...	...	...	(1)
Illinois	Sangamon	265	90+	...	...	...	...	(4)
Illinois	Knox	13.1	95+	...	...	...	...	(5)
Illinois	Knox	9.14	95+	...	...	...	...	(2)
Illinois	Hancock	2.9	82	16	1	...	1	(6)
Illinois	Henderson and Warren	18.0	84	8	8	...	...	(8)
Illinois	Adams and Pike	72.3	72	10	18	...	...	(8)
Wisconsin	Vernon and Monroe	28.0	47	11	42	...	...	(8)
Minnesota	Fillmore	37.5	87	4	9	...	...	(8)
Minnesota	Swift and Kandiyohi	87.7	100	...	...	...	...	(8)
Minnesota	Swift and Chippewa	319	100	...	...	...	...	(8)
Iowa	Lucas	14.2	74	20	5	1	...	(8)
Iowa	Mills	12.5	56	24	...	19	1	(8)
Iowa	Plymouth	13.6	100	...	...	...	...	(8)
Iowa	Sioux	9.1	100	...	...	...	...	(8)
Missouri	Johnson	19.7	69	21	3	7	...	(8)
Missouri	Lincoln	14.0	53	25	22	...	...	(8)
Kansas	Johnson	6.0	85	9	...	...	6	(9)
Mississippi	Marshall	0.166	35	65	...	...	...	(8)
Mississippi	Marshall	0.211	40	60	...	...	...	(8)
Mississippi	Marshall	0.071	15	85	...	...	...	(8)
Mississippi	Marshall	0.209	58	42	...	...	...	(8)
Mississippi	Lafayette	0.448	14	86	...	...	...	(8)
Mississippi	Lafayette	0.162	11	89	...	...	...	(8)
Mississippi	Lafayette	0.169	24	76	...	...	...	(8)
Mississippi	Lafayette	0.136	25	75	...	...	...	(8)
Mississippi	Lafayette	0.143	21	79	...	...	...	(8)
Mississippi	Carroll	0.154	73	27	...	...	...	(8)
Mississippi	Carroll	0.235	60	40	...	...	...	(8)
Mississippi	Carroll	0.360	69	31	...	...	...	(8)
Mississippi	Carroll	0.160	35	65	...	...	...	(8)
Mississippi	Yalobusha	0.125	23	77	...	...	...	(8)
Mississippi	Yalobusha	0.070	11	89	...	...	...	(8)
Mississippi	Yalobusha	0.199	24	76	...	...	...	(8)
Mississippi	Tate	0.063	26	74	...	...	...	(8)
Mississippi	Tate	0.159	65	35	...	...	...	(8)
Mississippi	Tate	0.121	47	53	...	...	...	(8)
Arkansas	Logan	4.1	77	15	8	...	...	(8)
Texas	Collin	3.71	92	5	3	...	...	(8)
Texas	Collin	2.63	95	4	1	...	...	(8)
Texas	Collin	2.39	92	3	5	...	...	(8)
Texas	Collin	1.91	88	8	4	...	...	(8)
Texas	Collin	1.19	78	11	11	...	...	(8)
Texas	Collin	1.02	92	5	3	...	...	(8)
Texas	Collin	1.01	91	7	2	...	...	(8)
Texas	Collin	0.80	93	4	3	...	...	(8)
Texas	Fayette	6.37	99	...	1	...	...	(8)
Texas	Fayette	5.63	99	...	1	...	...	(8)
Texas	Fayette	4.90	99	...	1	...	...	(8)
Texas	Fayette	2.12	98	...	2	...	...	(8)

TABLE 1 – *Continued*

Location		Size of drainage area	Relative sediment source					Reference[b]
State	County		Sheet	Gully	Stream channel	Valley trenching[a]	Other	
		sq mi	pct	pct	pct	pct	pct	
Texas	Dallas	2.31	98	1	1	...	...	(8)
Texas	Dallas	1.18	97	2	1	...	...	(8)
Texas	Dallas	0.76	94	4	2	...	...	(8)
Texas	Grayson	9.14	98	1	1	...	...	(8)
Texas	Grayson	5.68	91	8	1	...	...	(8)
Texas	Karnes	6.24	84	14	2	...	...	(8)
Texas	Karnes	2.84	95	2	3	...	...	(8)
Texas	Karnes	2.77	95	3	2	...	...	(8)
Texas	Karnes	1.35	78	14	8	...	...	(8)
Texas	Karnes	0.64	93	3	4	...	...	(8)
Texas	Bexar	5.43	96	1	3	...	...	(8)
Texas	Bexar	1.46	87	10	3	...	...	(8)
Texas	Bexar	1.36	89	4	7	...	...	(8)
Texas	Lee	8.9	100	...	...	...	...	(8)
Texas	Erath	3.6	98	...	2	...	...	(8)
Texas	Erath	2.5	99	0.5	0.5	...	...	(8)
Texas	Erath	1.8	95	5	...	...	...	(8)
Texas	Erath	2.0	100	...	...	...	...	(8)
Texas	Erath	1.6	100	...	...	...	...	(8)
Texas	Erath	3.2	99	...	1	...	...	(8)
Texas	Erath	6.0	98	1	1	...	...	(8)
Texas	Parker	0.92	97	2	1	...	...	(8)
Texas	Parker	0.98	92	4	4	...	...	(8)
Texas	Coleman	9.8	90	10	...	...	...	(8)
Texas	Coleman	2.4	100	...	...	...	...	(8)
Texas	Coleman	1.7	100	...	...	...	...	(8)
Texas	Coleman	1.0	95	5	...	...	...	(8)
Texas	Coleman	0.78	100	...	...	...	...	(8)
Texas	Coleman	0.69	100	...	...	...	...	(8)
Texas	Taylor	93.6	50	50	...	...	...	(8)
Texas	Taylor	34.0	90	10	...	...	...	(8)
Texas	Taylor	11.5	95	5	...	...	...	(8)
Texas	Taylor	0.95	100	...	...	...	...	(8)
Texas	Jones	252	90	10	...	...	...	(8)
Texas	Nolan	104	85	15	...	...	...	(8)
Texas	Fisher	32	80	20	...	...	...	(8)
Texas	Wilbarger	332	29	71	...	...	...	(8)
Texas	Wilbarger	2.4	35	65	...	...	...	(8)
Texas	Hardeman	40	40	60	..	...	...	(8)
Texas	Collingsworth	3.2	40	60	...	...	...	(8)
Texas	Throckmorton	6.3	95	5	...	...	...	(8)
Texas	Childress	13.7	90	10	...	...	...	(8)
Oklahoma	Washita	51.9	95	5	...	...	...	(8)
Oklahoma	Washita	22.2	90	10	...	...	...	(8)
Oklahoma	Washita	2.7	78	21	1	...	...	(8)
Oklahoma	Washita	0.7	95	3	2	...	...	(8)
Oklahoma	Washita	5.9	92	5	3	...	...	(8)
Oklahoma	Washita	1.5	98	1	1	...	...	(8)
Oklahoma	Washita	0.4	100	...	...	...	...	(8)
Oklahoma	Roger Mills	1.6	35	65	...	...	...	(8)
Oklahoma	Roger Mills	0.6	35	65	...	...	...	(8)
Oklahoma	Roger Mills	0.16	30	70	...	...	...	(8)
Oklahoma	Roger Mills	0.036	50	50	...	...	...	(8)
California	San Diego	112	56	...	...	44	...	(8)
California	Contra Costa	150	50	...	41	...	9	(8)

[a] Generally the entrenchment of ephemeral channels by headward advancement in alluvial plains as distinguished from upland gully erosion.

[b] For sources of data, see references at end of paper.

dates, from resurveys of previously established channel profiles and cross sections, from interviews with persons of long residence in an area and from other historical references and sources of information. The procedures are time consuming and laborious for large watersheds and may be limited in application for the lack of essential background and reference material.

Sediment delivery—In general, sediment-delivery rates for individual erosion processes are more difficult to establish than are estimates of erosion rates. It is recognized, of course, that not all of the material eroded in a watershed contributes immediately to downstream sediment problems. This is especially true of the products of sheet erosion, portions of which are often deposited at the base of slopes, along fence lines and field boundaries, on floodplains and in small upstream valleys. Inspection of most watersheds following erosive rains, or study of soils, will reveal extensive upland deposition and attest to the fact that a part of the eroded material is slow in reaching the main channels where many of the sediment problems occur.

There are no clear-cut and easily applied procedures for systematic tracing or routing of sediment through a watershed. This represents a distinct deficiency with respect to planning sediment control by means of watershed treatment. Nevertheless there are some guiding principles and general procedures which are useful in dealing with this problem.

In some watersheds the volume or quantity of gully and channel erosion is so small in comparison to sheet erosion that it is obviously of little consequence. In most watersheds it is more feasible to estimate a delivery rate for gully and channel sources than for sheet erosion.

Generally, material eroded from stream banks and beds, gullies, or other entrenched water courses is fed into larger channels, with less opportunity for deposition than is the case with the products of sheet erosion. With deeply incised gullies and channels, which overflow infrequently, it might be concluded that a high proportion of the sediment derived from the gullies and channels contributes directly to sediment yield of the watershed if the material is predominately fine textured. In large watersheds sediment delivery from erosion sources in the more remote parts of the drainage area should be scaled downward to reflect depositional opportunities between the source and points of damage downstream. For watersheds where an estimate can be made of the proportion of total sediment yield derived from gullies or channel sources, the proportion derived from sheet erosion can be estimated as the difference between total sediment yield and that derived from sources other than sheet erosion.

At best, the estimation of sediment delivery rates associated with erosion processes in a watershed is a difficult task and one with many frustrations, but the problem is basic to the determination of the kind of watershed treatment measures required for reduction of sediment yields and deserves our best efforts.

Examples of sediment sources—Estimates of relative sources of sediment comprising the sediment yield of watersheds, derived along the general procedures just outlined, have been made for a number of watersheds mostly east of the one-hundredth meridian. Results of studies on 113 watersheds, ranging in size from 23 ac to 437 sq mi, are summarized in Table 1.

In half of these watersheds, sheet erosion accounts for 90 pct or more of the sediment yield. It accounts for 75 pct or more of the sediment in 73 of the 113 cases. Sheet erosion is the source of 50 pct or more of the sediment in 89 of the watersheds. In 105 of the cases reported, sheet erosion contributes more than 25 pct of the sediment yield.

Sheet erosion is clearly the dominant source of sediment in most of the watersheds listed in Table 1. It is believed that this is generally the case in the more humid parts of the country. Note, however, that the proportion of sediment yield supplied by sheet erosion ranges from 11 to 100 pct among the watersheds cited. This wide range in sediment sources emphasizes the fact that watersheds have their individual characteristics and must be considered individually with respect to sources of sediment as well as sediment yield.

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Importance of Channel Erosion as a Source of Sediment

ALBERT E. COLDWELL

Abstract—A specific statement is not possible as to the percentage of total erosion caused by channel erosion. Watersheds containing tight soil may be almost entirely free of gullies, streams may have deep and narrow channels with stable banks, and slopes may be small, resulting in little bed movement. On the other hand, watersheds draining upland sandy areas may have many gullies with rapid headward movement; channels may be shallow and wide, with such widening actively increasing at the present time; and steep slopes may cause a considerable amount of bed movement. Combinations of these factors may occur in a single watershed. Absence of sediment measuring stations on gullies makes volumetric estimates based on rate of change in depth, width, and headward movement necessary. Establishment of valley and channel range profiles is helpful in estimating bank erosion. It is being found that aerial photographs taken some years apart indicate that bank erosion may cause a greater part of the erosion in a watershed than was previously supposed. Confirmation of this is indicated by relatively permanent shifts in discharge rating curves. For bed movement reliance must be placed on current research and established formulas.

Channel erosion is popularly considered as being the erosion which occurs after runoff water has left the uplands. Gully erosion would fall in this classification on the basis that a continuous stream channel begins at the base of a gully overfall. Other sources of channel erosion would be streambank and streambed erosion [*Lane* and *Borland*, 1951].

In the absence of reference to a certain area under consideration and detailed surveys thereof, it is not advisable to make a specific statement as to the proportion of total erosion which is caused by channel erosion. An example might be found of a mountainous stream with gravel bottom, where runoff water is nearly always clear and the only erosion is the gradual downstream movement of the gravel in the bed. In this case virtually 100 pct of the total erosion would be channel erosion. On the other hand, water flowing through a large swampy area during flood periods might be carrying only a load of suspended material obtained from sheet erosion, in which case the contribution of channel erosion would be virtually zero.

To expand on this thought further, a watershed draining certain types of tight soil may be almost entirely free of gullies and the main stream might have a typically deep and narrow channel with fairly stable banks. The stream gradient might be rather gentle, so that there would be very little movement of material along the streambed. This watershed, however, might be located in an area of abundant rainfall where sheet erosion is a problem. In this case, the contribution of channel erosion to total erosion would be minor.

Consideration might then be given to a watershed draining an upland sandy area, where gullies are deep and unstable. Each rain causes further movement of the heads of gullies towards the top of the drainage area divide. The main stem in such an area might be shallow and wide, with such widening now actively occurring. The stream slope might be steep, thus causing a considerable amount of bed movement. Such a watershed could be located in an area of limited, though torrential, rainfall. Under such conditions the contribution of channel erosion to the total erosion would be great.

A combination of several of these varying types of channel erosion would be found in the major river basins in which sedimentation is a problem.

In the classification of gullies should be included such types of erosion as valley trenches, arroyos, and 'snoots,' as they are called in Africa. A thorough sampling of the sediment load resulting from gully erosion would require an investigational program that would be cumbersome and impracticable. Dependence must be placed upon methods for obtaining the volume of gully erosion from such sources as topographic maps and other types of surveys. Examples of such surveys or estimates are available in the literature [*Leopold*, 1946, p. 1260; *Brune*, 1951, p. 61].

Relatively accurate estimates of bank erosion can be made if a system of channel and valley profiles is established in the valley under study. These range profiles should be surveyed so that they cross the valley at right angles, and it is usually also desirable for them to be perpendicular to the

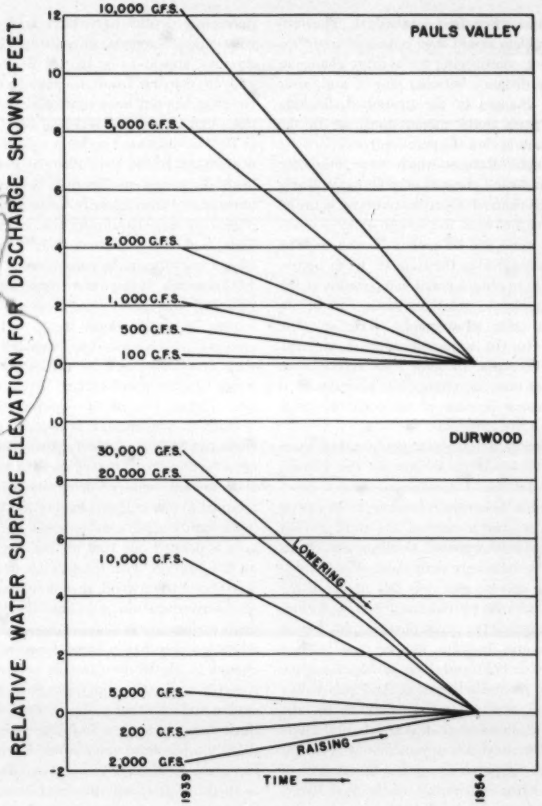
stream channel when first established. Theoretically, the problem would then consist of resurveying the ranges, multiplying the average change in areas by the distance between ranges, and, after allowing for changes in the streambed, drawing conclusions from these computations as to the volume of bank caving. In practice, conditions are not this simple. Ranges which were originally perpendicular to the channel may be more nearly parallel to the channel when the resurvey is made. Close coordination with the survey party is desirable, so that notes will be made as to the angle at which the range crosses the channel. Even better, if it is feasible to obtain aerial photographs at the time of each survey, great assistance can be obtained from such photographs. Trigonometric adjustments to the apparent amount of bank erosion can be made. In some cases results from certain ranges must be temporarily abandoned in the computations because of too small an angle between range and channel.

Examination of aerial photographs taken some years apart shows that, at least in the Central Lowlands and Great Plains physiographic provinces with which the writer is familiar, bank caving is furnishing a greater part of the total erosion than was previously supposed. Confirmation of this is indicated by relatively permanent shifts in discharge rating curves, and it is this phase of the problem which will be discussed before further reference is made to the aerial photographs. Figure 1 is a schematic diagram showing the relative change between 1939 and 1954 in water surface elevations for given discharges at the Pauls Valley and Durwood stream gaging stations on the Washita River, in south-central Oklahoma. Pauls Valley and Durwood are approximately 146 and 63 river miles, respectively, above the mouth of the Washita River, a tributary of the Red River. The Washita River arm of Lake Texoma, formed by Denison Dam across the Red River, is immediately downstream from the Durwood gage, but at top of power pool elevation the lake is about 20 river miles downstream from the gage.

The irregularities in the relative water surface elevations during the period 1939 to 1954 are not shown on the diagram, but in general it is to be seen that for the higher discharges the depth of water during the period has significantly decreased. These gages are located on bridges, and to some extent throughout the years the width and area of the channel at the bridges have been artificially controlled. At the gage locations themselves, the decreasing depths have been accompanied by a considerable increase in velocity. However, this does not appear to be true of the river upstream and downstream from the gage locations. Where the river has not been controlled there are indications that its channel width of from 100 to 150 ft in 1939 has increased rather consistently to a width of from 200 to 350 ft in 1954. As indicated by the lower discharges on Figure 1, the widening of the uncontrolled river appears not to have been accompanied by any significant rise in the streambed. This would be consistent with an application of Manning's formula to conditions in the 1939 and 1954 channels. If the wider stream at a given elevation had the same cross-sectional area as previously, it would simply mean that the material eroded from the banks had deposited in the stream with a resultant rise in streambed elevation, in which case the water-surface elevation would have been higher, instead of significantly lower as it actually is. Therefore, it is strongly indicated that there has been a relatively permanent increase in cross-sectional area throughout the years, and that the material removed from the banks has contributed to the sediment load of the Washita River in the reach under consideration.

It is pointed out that all the discharges shown on the diagram, with the possible exception of the 30,000 cfs at Durwood, now flow within the banks of the river and do not cause flooding. Over the years an increase in channel capacity has occurred, which possibly has reduced frequency of flooding enough to constitute a benefit to be considered as somewhat offsetting the damaging effects of bank caving and resulting sediment load of the stream. Stated another way, a discharge which is now just slightly below flood stage would have been several feet above flood stage 15 years ago. It is interesting to speculate as to whether land owners benefiting by such improved conditions realize that the conditions exist.

As discussed previously, examination of the aerial photographs (Fig. 2) of the Washita River in the vicinity of the Durwood gage, taken in 1936 and again in 1951 shows in the earlier pictures a channel about 125 ft wide, lined almost solidly with a luxuriant growth of trees compared to a channel in the later pictures about 250 ft wide (locally as much as 700 ft wide) from which many of the trees along the banks have disappeared. A hint of what was to follow is shown in the 1936 pictures, where bank caving was occurring on widely isolated bends of the river. These stretches,



Durwood, Washita River, Oklahoma, between 1939 and 1954

FIG. 1 – Change in ratings of stream-gaging stations near Pauls Valley and Durwood, Washita River, Oklahoma between 1939 and 1954

bare of trees, were generally only a few hundred yards long. Fifteen years later the bank caving was more closely spaced, on straight reaches of river as well as on bends. Similar conditions have been reported from several different locations throughout the entire 626-mile length of the Washita River. Other incidental, though somewhat extraneous, things to be noted from the comparisons of aerial photographs are the recent improvements in highway design and the spread of land treatment measures upon the face of the land. In one case a seriously developing gully has now been plugged in two places with small detention dams, forming two farm ponds on land which would otherwise be of little use.

The problem of streambed erosion is one for which there is a continual demand for quantitative answers, but upon which there does not appear

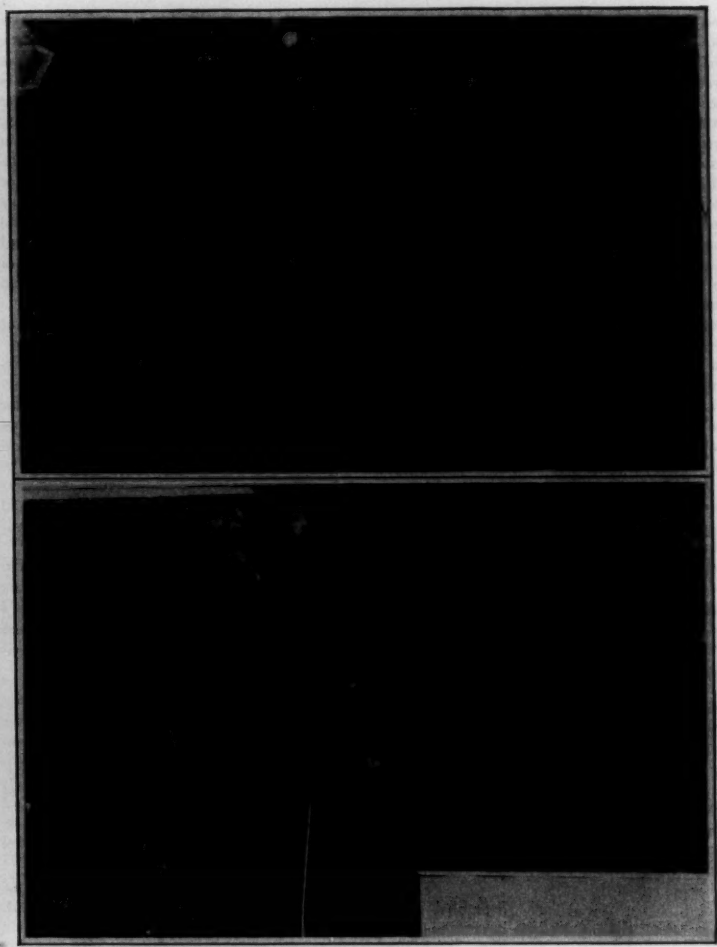


FIG. 2 – Aerial photographs of Washita River in vicinity of Durwood gaging station, Oklahoma; taken in 1936 (upper view) and in 1951 (lower view)

to be general agreement as to the accuracy of such answers. Research is continuing on the subject of bed load and during the past few years increasing emphasis has been placed upon formulas for determination of total load as well as only the bed-load portion. It must be recognized in the discussion of channel erosion that a particle of soil which was eroded by gully erosion during one storm might be eroded by bank erosion years later and by bed erosion at an even later time. This appears to be

good justification for considering total sediment load throughout a watershed instead of trying to subdivide it too finely. In spite of the lack of agreement among bed-load formulas, from the research certain concepts are beginning to stand out so strongly and so frequently that some of the mystery concerning bedload may be on the way to solution.

The Einstein bed-load formula is one that is contributing greatly toward solution of these problems. Based upon the size of material in the bed of a stream, the formula definitely identifies the amount of such material which should move along the streambed, and the amount which should be thrown up into the flowing water to become part of the suspended load. When using the formula for the first time, one may get the impression that it is a miracle formula, for before any results concerning sediment loads are obtained, the formula defines a discharge rating curve for the river under study, which agrees surprisingly well with actual discharge observations. After further consideration, it is then realized that the same thing could be done by any commonly used hydraulic open-channel formula with the same set of slope and channel characteristics except that the Einstein formula substitutes grain-size characteristics for roughness coefficients. This, then, supports a tentative conclusion that the formula is strictly applicable only for discharges that are within banks and could not be used where overbank vegetation (or occasionally even channel vegetation) would be a factor in the roughness coefficient. Actually, this tentative conclusion was reached by the writer after it was noted that, at two locations where the formula was used for computations of bed load and total load, the portion of sediment computed as being in suspension, for various discharges of less than bankfull capacity, agreed to some extent with the amount indicated by the lowest suspended sediment concentrations ever sampled at the same locations and discharges. These are considered to be the samples which were virtually free of wash load when collected.

For discharges near and above bankfull capacity, it was found that the Einstein formula appeared to give suspended sediment amounts considerably greater than indicated by the collected samples with low concentrations. It is possible that the formula, therefore, is not flexible enough to care for the exactly opposite things that are occurring during moderate and major floods, namely, that the river bed material is going into suspension where velocities are high, but part of the same material is being settled out in the low velocities in the overbank and backwater areas. Examples of such conditions have been noted close to river banks following floods, where sand splays or dunes, consisting of material not greatly different from that in the stream bed, have been deposited on the banks high above the stream bed. While it is not within the province of this paper to evaluate the Einstein formula or any of the other bed-load formulas in a thorough manner, it is suggested that there may be limits as to the applicability of a single formula for both bed-load and total-load computations.

Assuming that in some sand-bed streams a great proportion of the bed material is carried into suspension during high water, it may be found practicable to reduce the total sediment load of a watershed by reducing channel erosion. Slope is a factor included in all of the generally recognized bed-load formulas [*Colby* and *Hembree*, 1955, p. 114]. Extensive studies would be necessary to determine the economic value of such features as vegetative screens, permeable dikes, dumped rock dams, and other structures which would act as major detention dams and thus reduce the slope.

In summary, contrasted to gully erosion and streambank erosion, where direct methods are available for measuring their quantities, estimates of streambed erosion must be based upon past and current research and upon the best of the bed-load formulas developed therefrom.

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Quantitative Analysis of Watershed Geomorphology

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Abstract—Quantitative geomorphic methods developed within the past few years provide means of measuring size and form properties of drainage basins. Two general classes of descriptive numbers are (1) linear scale measurements, whereby geometrically analogous units of topography can be compared as to size; and (2) dimensionless numbers, usually angles or ratios of length measures, whereby the shapes of analogous units can be compared irrespective of scale.

Linear scale measurements include length of stream channels of given order, drainage density, constant of channel maintenance, basin perimeter, and relief. Surface and cross-sectional areas of basins are length products. If two drainage basins are geometrically similar, all corresponding length dimensions will be in a fixed ratio.

Dimensionless properties include stream order numbers, stream length and bifurcation ratios, junction angles, maximum valley-side slopes, mean slopes of watershed surfaces, channel gradients, relief ratios, and hypsometric curve properties and integrals. If geometrical similarity exists in two drainage basins, all corresponding dimensionless numbers will be identical, even though a vast size difference may exist. Dimensionless properties can be correlated with hydrologic and sediment-yield data stated as mass or volume rates of flow per unit area, independent of total area of watershed.

Introduction—Until about ten years ago the geomorphologist operated almost entirely on a descriptive basis and was primarily concerned with the history of evolution of landforms as geological features. With the impetus given by *Horton* [1945], and under the growing realization that the classical descriptive analysis had very limited value in practical engineering and military applications, a few geomorphologists began to attempt quantification of landform description.

This paper reviews progress that has been made in quantitative landform analysis as it applies to normally developed watersheds in which running water and associated mass gravity movements are the chief agents of form development. The treatment cannot be comprehensive; several lines of study must be omitted. Nevertheless, this paper may suggest what can be done by systematic approach to the problem of objective geometrical analysis of a highly complex surface.

Most of the work cited has been carried out at Columbia University over the past five years under a contract with the Office of Naval Research, Geography Branch, Project NR 389-042 for the study of basic principles of erosional topography. References cited below give detailed explanations of techniques and provide numerous examples taken from field and map study.

Dimensional analysis and geometrical similarity—We have attempted to base a system of quantitative geomorphology on dimensional analysis and principles of scale-model similarity [*Strahler*, 1954a, p. 343; 1957]. Figure 1 illustrates the concept of geometrical similarity, with which we are primarily concerned in topographical description. Basins A and B are assumed to be geometrically similar, differing only in size. The larger may be designated as the prototype, the smaller as the model. All measurements of length between corresponding points in the two basins bear a fixed scale ratio, λ. Thus, if oriented with respect to a common center of similitude, the basin mouths Q′ and Q are located at distances r′ and r, respectively, from C; the ratio of r′ to r is λ. In short, all corresponding length measurements, whether they be of basin perimeter, basin length or width, stream length, or relief (h′ and h in lower profile), are in a fixed ratio, if similarity exists.

All corresponding angles are equal in prototype and model (Fig. 1). This applies to stream junction angles α' and α, and to ground slope angles β' and β. Angles are dimensionless properties; hence the generalization that in two geometrically similar systems all corresponding dimensionless numbers or products describing the geometry must be equal.

Studies of actual drainage basins in differing environments show that in many comparisons in homogeneous rock masses, geometrical similarity is closely approximated when mean values are considered, whereas in other comparisons, where geologic inhomogeneity exists, similarity is def-

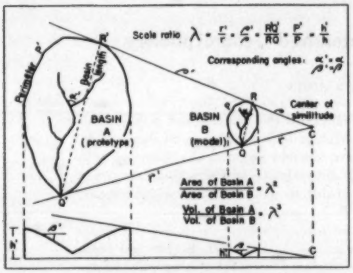
Scale ratio
Corresponding angles
Prototype
Basin axis
BASIN A (prototype)
BASIN B (model)
Center of similitude
Area of Basin A / Area of Basin B = λ²
Vol. of Basin A / Vol. of Basin B = λ³

FIG. 1. – Principles of dimensional analysis and geometrical similarity applied to drainage basins

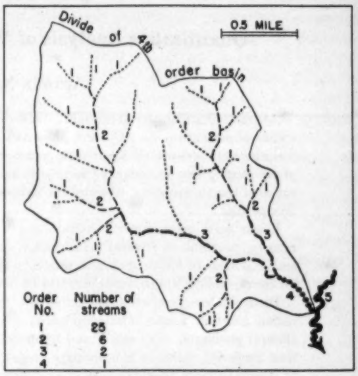

FIG. 2 – Method of designating stream orders (Strahler, 1954a, p. 344)

inately lacking [*Strahler*, 1957]. One advantage of using the principles of similarity as a basis of operations is that it focuses attention upon (a) linear scale differences that are independent of form or shape properties, and (b) form differences existing independently of size differences.

The remainder of this paper describes certain landform properties that are dimensionless; others that have dimensions of length or length products and which serve as scale-of-size indicators. Apart from systematizing the analysis, this information is useful in formulation of rational equations relating geomorphic properties to various related or controlling factors with which a significant regression may be expected.

Order analysis—The first step in drainage basin analysis is order designation, following a system only slightly modified from *Horton* [1945, p. 281–282] (Fig. 2). Assuming that the channel-network map includes all intermittent and permanent flow lines located in clearly defined valleys, the smallest finger-tip tributaries are designated Order 1. Where two first-order channels join, a channel segment of Order 2 is formed; where two of Order 2 join, a segment of Order 3 is formed; and so forth. The trunk stream through which all discharge of water and sediment passes is therefore the stream segment of highest order.

Any usefulness which the stream order system may have depends upon the premise that on the average, if a sufficiently large sample is treated, order number is directly proportional to relative watershed dimensions, channel size, and stream discharge at that place in the system. Also, because order number is dimensionless, two drainage basins differing greatly in linear scale can be equated or compared with respect to corresponding points in their geometry through use of order number. The first step in drainage-network analysis is the counting of stream segments of each order. This is followed by analysis of the way in which numbers of stream segments change with increasing order.

Bifurcation ratio—Horton's [1945, p. 291] law of stream numbers states that the numbers of stream segments of each order form an inverse geometric sequence with order number. This is generally verified by accumulated data [*Strahler*, 1952, p. 1137; *Schumm*, 1956, p. 603] and is conveniently treated as shown in Figure 3. A regression of logarithm of number of streams of each order (ordinate) on stream order (abscissa) generally yields a straight-line plot with very little scatter [*Maxwell*, 1955]. Even though the function relating these variables is defined only for integer values of the independent variable, a regression line is fitted; the slope of the line, or regression coefficient b is used. The anti-logarithm of b is equivalent to Horton's bifurcation ratio r_b and in this case has the value of 3.52. This means that on the average there are three and one-half times as many streams of one order as of the next higher order.

One might think that the bifurcation ratio would constitute a useful dimensionless number for expressing the form of a drainage system. Actually the number is highly stable and shows a small range of variation from region to region or environment to environment, except where powerful geologic controls dominate. *Coates* [1956, Table 3]

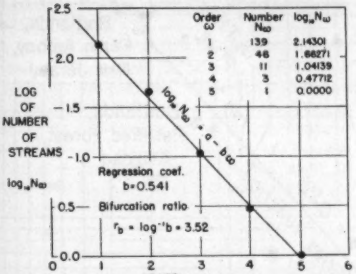

FIG. 3 – Regression of number of stream segments on stream order; data from *Smith* (1953, Plate 8)

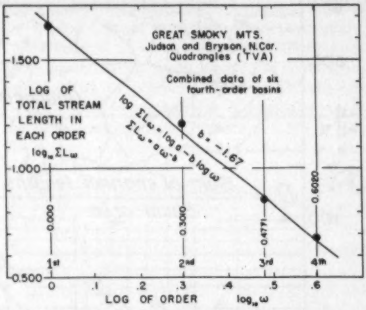
GREAT SMOKY MTS.
Judson and Bryson, N.Car. Quadrangles (TVA)
Combined data of six fourth-order basins
LOG OF TOTAL STREAM LENGTH IN EACH ORDER
logₑ ΣLω = logₑ a − b logₑ ω
b = −1.67
LOG OF ORDER logₑ ω
1st
2nd
3rd
4th

FIG. 4 – Regression of stream length on stream order; stream lengths of six fourth-order basins have been summed for each order to reduce effects of chance variations.

found bifurcation ratios of first-order to second-order streams to range from 4.0 to 5.1; ratios of second-order to third-order streams to range from 2.8 to 4.9. These values differ little from *Strahler's* [1952, p. 1134].

Frequency distribution of stream lengths—Length of stream channel is a dimensional property which can be used to reveal the scale of units comprising the drainage network. One method of length analysis is the measurement of length of each segment of channel of a given stream order. For a given watershed these lengths can be studied by frequency distribution analysis [*Schumm*, 1956, p. 607]. Stream lengths are strongly skewed right, but this may be largely corrected by use of logarithm of length. Arithmetic mean, estimated population variance, and standard deviation serve as standards of description whereby different drainage nets can be compared and their differences tested statistically [*Strahler*, 1954b].

Relation of stream length to stream order—Still another means of evaluating length relationships in a drainage network is to relate stream length to stream order. A regression of logarithm of total stream length for each order on logarithm of order may be plotted (Fig. 4). Again, the function is defined only for integer values of order. Several such plots of length data made to date seem to yield consistently good fits to a straight line, but the general applicability of the function is not yet established, as in the case of the law of stream numbers.

The slope of the regression line b (Fig. 4) is the exponent in a power function relating the two variables. Marked differences observed in the exponent suggest that it may prove a useful measure of the changing length of channel segments as order changes. Because this is a nonlinear variation, the assumption is implicit that geometrical similarity is not preserved with increasing order of magnitude of drainage basin.

Drainage basin areas—Area of a given watershed or drainage basin, a property of the square of length, is a prime determinant of total runoff or sediment yield and is normally eliminated as a variable by reduction to unit area, as in annual sediment loss in acre-feet per square mile. In order to compare drainage basin areas in a meaningful way, it is necessary to compare basins of the same order of magnitude. Thus, if we measure the areas of drainage basins of the second order, we are measuring corresponding elements of the systems. If approximate geometrical similarity exists, the area measurements will then be indicators of the size of the landform units, because areas of similar forms are related as the square of the scale ratio.

Basin area increases exponentially with stream order, as stated in a law of areas [*Schumm*, 1956, p. 606], paraphrasing Horton's law of stream lengths.

Schumm [1956, p. 607] has shown histograms of the areas of basins of the first and second orders and of patches of ground surface too small to have channels of their own. Basin area distributions are strongly skewed, but this is largely corrected by use of log of area. Area is measured by planimeter from a topographic map, hence represents projected, rather than true surface area. Estimation of true surface area has been attempted where surface slope is known [*Strahler*, 1956a, p. 579].

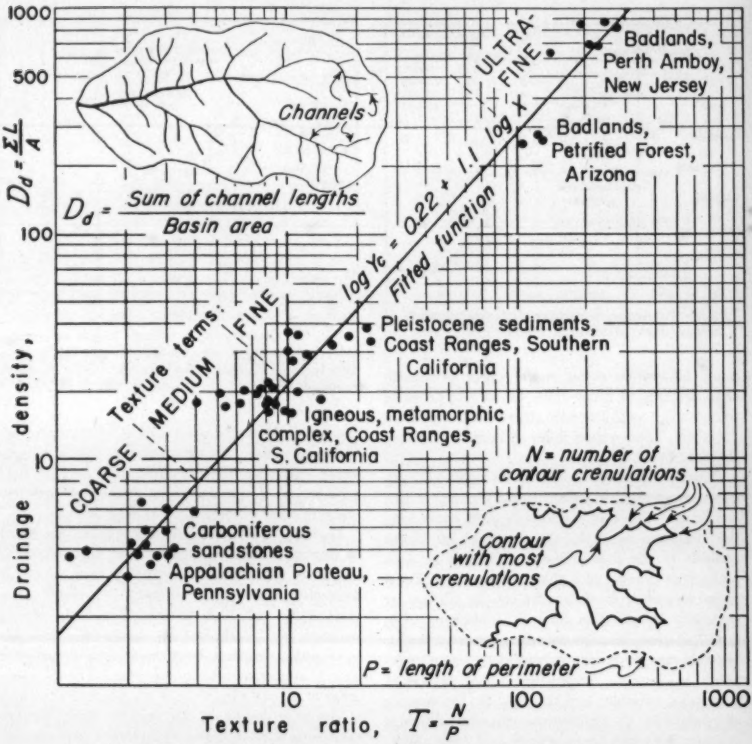

FIG. 5 – Definitions of drainage density and texture ratio (Strahler, 1954a, p. 348)

Drainage density and texture ratio—An important indicator of the linear scale of landform elements in a drainage basin is drainage density, defined by *Horton* [1945, p. 283]. The upper left-hand corner of Figure 5 shows the definition of drainage density as the sum of the channel lengths divided by basin area. Division of length by area thus yields a number with the dimension of inverse of length. In general, then, as the drainage density number increases, the size of individual drainage units, such as the first-order drainage basin, decreases proportionately.

Figure 5 shows the relation between drainage density and a related index, the texture ratio, defined by *Smith* [1950]. Because the contour inflections on a good topographic map indicate the existence of channels too small to be shown by stream symbols, their frequency is a measure of closeness of channel spacing and hence also correlates with drainage density.

Drainage density is scaled logarithmically on the ordinate of Figure 5. The grouped points in the lower left-hand corner of the graph represent basins in resistant, massive sandstones. Here the streams are widely spaced and density is low. The next group of points encountered represents typical densities in deeply weathered igneous and metamorphic rocks of the California coast ranges. In the extreme upper right are points for badlands, where drainage density is from 200 to 900 miles of

channels per square mile [*Smith*, 1953; *Schumm*, 1956, p. 612].

Because of its wide ratio of variation, drainage density is a number of primary importance in landform scale analysis. One might expect that sediment yield would show a close positive relationship with drainage density. A rational theory of the relation of drainage density to erosion intensity, predicting the morphological changes to be expected when ground surface resistance is lowered by land use, has been outlined by *Strahler* [1956*b*].

Constant of channel maintenance—Schumm [1956, p. 607] has used the inverse of drainage density as a property termed constant of channel maintenance. In Figure 6 the logarithm of basin area (ordinate) is treated as a function of logarithm of total stream channel length (abscissa). Stream length is cumulative for a given order and includes all lesser orders; it is thus the total channel length in a watershed of given order. Length in this case is projected to the horizontal plane of the map; true lengths would be obtained by applying a correction for slope.

An individual plotted point on the graph represents a given stream order in the watershed, as numbered 1 through 5. Using data of the three examples given by Schumm, the sets of points fall close to a straight line of 45° slope; thus the relationship is treated as linear even though plotted here on log-log paper. If the logarithm of the intercept is read at log stream length = 0, and the antilog of this intercept is taken, we obtain the constant of channel maintenance C which is actually the slope of a linear regression of area on length.

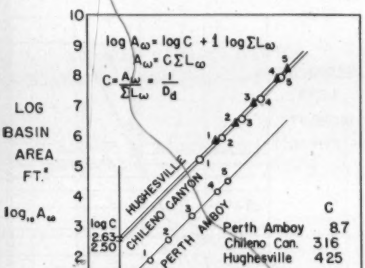

FIG. 6 – Constant of channel maintenance, C. Data replotted on logarithmic scales from *Schumm* (1956, p. 606)

The value of C = 8.7 in the Perth Amboy badlands means that on the average 8.7 sq ft of surface are required to maintain each foot of channel length. In the second example, Chileno Canyon in the California San Gabriel Mountains, 316 sq ft of surface are required to maintain one foot of channel length.

The constant of channel maintenance, with the dimensions of length, is thus a useful means of indicating the relative size of landform units in a drainage basin and has, moreover, a specific genetic connotation.

Maximum valley side slopes—Leaving now the drainage network and what might be classified as planimetric or areal aspects of drainage basins, we turn to slope of the ground surface. This brings into consideration the aspect of relief in drainage basin geometry. One significant indicator of the over-all steepness of slopes in a watershed is the maximum valley-side slope, measured at intervals along the valley walls on the steepest parts of the contour orthogonals running from divides to adjacent stream channels.

Maximum valley-side slope has been sampled by several investigators in a wide variety of geological and climatic environments [*Strahler*, 1950; *Smith*, 1953; *Miller*, 1953; *Schumm*, 1956; *Coates*, 1956; *Melton*, 1957]. Within-area variance is relatively small compared with between-area differences. This slope statistic would therefore seem to be a valuable one which might relate closely to sediment production.

Mean slope curve—Another means of assessing the slope properties of a drainage basin is through the mean slope curve [*Strahler*, 1952, p. 1125–1128]. This requires the use of a good contour topographic map. The problem is to estimate the average, or mean slope of the belt of ground surface lying between successive contours. This may be done by measuring the area of each contour belt with a planimeter and dividing this area by the length of the contour belt to yield a mean width. The mean slope will then be that angle whose tangent is the contour interval divided by the mean belt width. Mean slope of each contour interval is plotted from summit point to basin mouth. Curves of this type will differ from region to region, depending upon geologic structure and the stage of development of the drainage system. If the mean slope for each contour belt is weighted for per cent of total basin surface area, it is possible

to arrive at a mean slope value for the surface of the watershed as a whole.

Slope maps—Another means of determining slope conditions over an entire ground surface of a watershed is through the slope map [*Strahler*, 1956a]. (1) A good topographic map is taken. (2) On this map the slope of a short segment of line normal to the trend of the contours is determined at a large number of points. These may be recorded as tangents or sines, depending upon the kind of map desired. (3) These readings are contoured with lines of equal slope, here called isotangents. (4) The areas between successive isotangents are measured with a planimeter and the areas summed for each slope class. (5) This yields a slope frequency percentage distribution. Because the entire ground surface has been analyzed, the mean, standard deviation, and variance are treated as population parameters, at least for purposes of comparison with small samples taken at random from the same area.

Lines of equal sine of slope, or isosines, may also be drawn. The interval between isosines on the map becomes the statistical class on the histogram. Sine values are designated as g values because the sine of slope represents that proportion of the acceleration of gravity acting in a downslope direction parallel with the ground surface.

Rapid slope sampling—The construction of slope maps and their areal measurement is extremely time-consuming. Experiments have shown that essentially the same information can be achieved by random point sampling [*Strahler*, 1956a, p. 589–595]. Both random coordinate-sampling and grid sampling have been tried. In the random-coordinate method a sample square is scaled in 100 length units per side. From a table of random numbers the coordinates of sample points are drawn for whatever sample size is desired. The grid method does much the same thing, but is not flexible as to sample size.

Point samples, which are easy to take, were compared with the frequency distribution measured from a slope map. Noteworthy is the extremely close agreement in means and variances, and even in the form of the frequency distributions, including a marked skewness. Tests of sample variance and mean are discussed by *Strahler* [1956a].

Chapman [1952] has developed a method of analyzing both azimuth and angle of slope from contour topographic maps. Although based on petrofabric methods and designed largely for use in geological analysis of terrain, the method might be applied to a watershed as a means of assessing both slope steepness and orientation simultaneously.

Relief ratio—Schumm [1956, p. 612] has devised and applied a simple statistic, the relief ratio, defined as the ratio between total basin relief (that is, difference in elevation of basin mouth and summit) and basin length, measured as the longest dimension of the drainage basin. In a general way, the relief ratio indicates overall slope of the watershed surface. It is a dimensionless number, readily correlated with other measures that do not depend on total drainage basin dimensions. Relief ratio is simple to compute and can often be obtained where detailed information on topography is lacking.

Schumm [1954] has plotted mean annual sediment loss in acre feet per square mile as a function of the relief ratio for a variety of small drainage basins in the Colorado Plateau province [Fig. 7]. The significant regression with small scatter suggests that relief ratio may prove useful in estimating sediment yield if the parameters for a given climatic province are once established.

Hypsometric analysis—Hypsometric analysis, or the relation of horizontal cross-sectional drainage basin area to elevation, was developed in its modern dimensionless form by *Langbein* and others [1947]. Whereas he applied it to rather large watersheds, it has since been applied to small drainage basins of low order to determine how the mass is

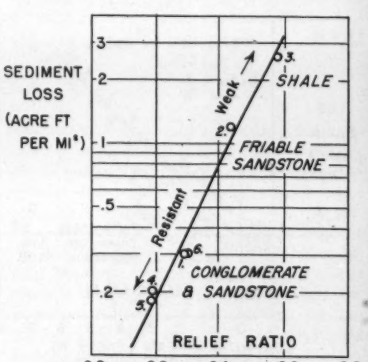

FIG. 7 – Regression of sediment loss on relief ratio, after *Schumm* (1954, p. 218)

distributed within a basin from base to top [*Strahler*, 1952; *Miller*, 1953; *Schumm*, 1956; *Coates*, 1956].

Figure 8 illustrates the definition of the two dimensionless variables involved. Taking the drainage basin to be bounded by vertical sides and a horizontal base plane passing through the mouth, the relative height is the ratio of height of a given contour h to total basin height H. Relative area is the ratio of horizontal cross-sectional area a to entire basin area A. The percentage hypsometric curve is a plot of the continuous function relating relative height y to relative area x.

As the lower right-hand diagram of Figure 8 shows, the shape of the hypsometric curve varies in early geologic stages of development of the drainage basin, but once having attained an equilibrium, or mature stage (middle curve on graph), tends to vary little thereafter. Several dimensionless attributes of the hypsometric curve are measurable and can be used for comparative purposes. These include the integral, or relative

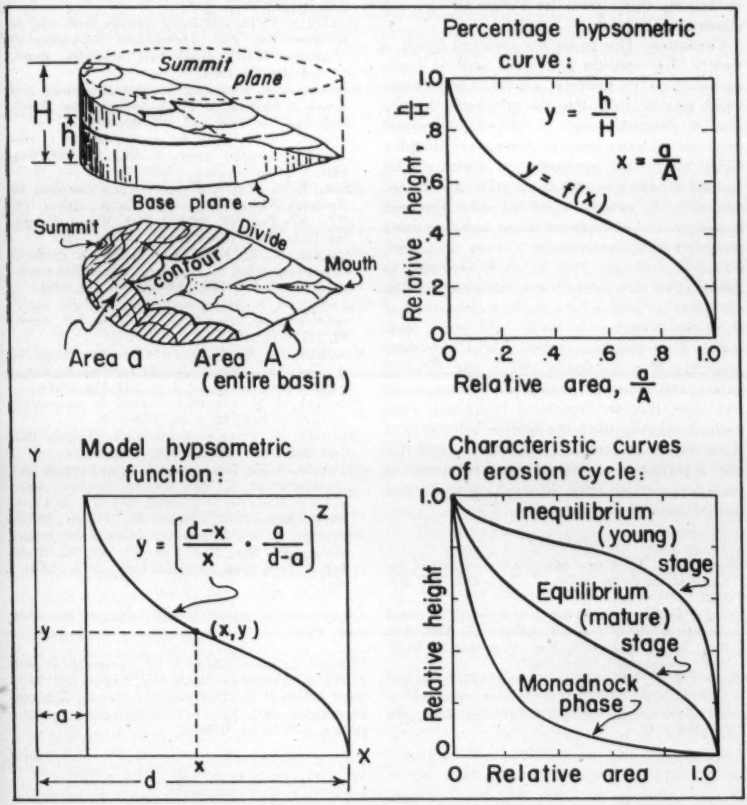

FIG. 8 – Method of hypsometric analysis (Strahler, 1954a, p. 353)

area lying below the curve, the slope of the curve at its inflection point, and the degree of sinuosity of the curve. Many hypsometric curves seem to be closely fitted by the model function shown in the lower left corner of Figure 8, although no rational or mechanical basis is known for the function.

Now that the hypsometric curves have been plotted for hundreds of small basins in a wide variety of regions and conditions, it is possible to observe the extent to which variation occurs. Generally the curve properties tend to be stable in homogeneous rock masses and to adhere generally to the same curve family for a given geologic and climatic combination.

Conclusion—This paper has reviewed briefly a variety of geometrical properties, some of length dimension or its products, others dimensionless, which may be applied to the systematic description of drainage basins developed by normal processes of water erosion. Among the morphological aspects not mentioned are stream profiles and the geometry of stream channels. These, too, are subject to orderly treatment along the lines suggested. The examples of quantitative methods presented above are intended to show that, complex as a landscape may be, it is amenable to quantitative statement if systematically broken down into component form elements. Just which of these measurements or indices will prove most useful in explaining variance in hydrological properties of a watershed and in the rates of erosion and sediment production remains to be seen when they are introduced into multivariate analysis. Already there are definite indications of the usefulness of certain of the measures and it is only a matter of continuing the development of analytical methods until the most important geomorphic variables are isolated.

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Relating Sediment Yield to Watershed Variables

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Abstract—The yield of sediment from watersheds depends upon three sets of variables: (1) inherent watershed characteristics such as geology and topography; (2) land use, condition of vegetation, and management and protective measures; and (3) nature of storms and streamflow which produce and transport sediment. Measured quantities of yield also depend on the sediment measuring device and on which fraction of total sediment yield is measured. The sources of variation in sediment yield between and within watersheds can be evaluated by study of the yield from many watersheds which have wide differences in variables affecting sediment yields. Such studies are useful to determine and evaluate the principal sources of sediment, to evaluate the probable effects of conservation programs on yield, and to provide criteria for design of reservoirs and channels. This paper summarizes some recent studies in which multiple regression analysis was used in relating sediment yield to watershed variables. The studies are discussed in the light of methods of selecting watersheds, data, variables, and functions; and the effects of neglected variables, errors in variables, and exclusion of nonsignificant variables.

Introduction—Many hydrologic processes operate within watersheds, and operate on highly variable 'material,' with highly variable results. As a consequence, we have some difficulty in working out the end results, say the sediment yield, of all these processes operating on each piece of a watershed. Also, when we know the sediment yield, we have equal difficulty in determining the share each process contributed to that yield. We need to predict sediment yield in order to design reservoirs and channels; we need to analyze the processes and the contributions of sediment from parts of watersheds in order to locate the sediment sources and evaluate how effective treatment of those sources would be in reducing sedimentation.

Several research workers have found that multiple regression analysis offers a way out of this difficulty. This paper reviews some of those studies to see how multiple regression has been found useful and some ways to make the technique more useful.

Why is multiple regression analysis used in sediment yield studies? It tells us two things we want to know: how the parts and characteristics of watersheds contribute to sediment yield, and how well we can predict the yield from the whole watershed by study of the parts. The possible errors in each are evaluated in an unbiased way, giving us a measure of how good the results are and some clues as to where to look for improvement.

The studies which this paper reviews and discusses were based on the hypothesis that sediment yield from whole watersheds is proportional to the values of variables of the watershed and the sediment catching device. Log transformations were made in the data before analyses. Why log transformations of the data? For two chief reasons. First, the quantitative effect on sediment yield of a change in any one variable depends on the values of each other variable. Second, the variability of sedimentation is generally proportional to the magnitude of the causative variables. When the first is true, the log transformation gives the simplest form of the function. When the second is true, the log transformation gives a more valid estimate of error over the whole range of estimated sedimentation.

In relating sediment yield from watersheds to its causes it is helpful to consider three major groups of variables as being involved: (1) The hydrologic events, the storms and streamflow, which are producing and transporting sediment. (2) The watershed conditions and land use variables, which are changeable and changing with time. (3) The inherent watershed variables, which are essentially constant throughout time, such as area, geology, and physiography. Involved also is the sediment measuring device and its efficiency, the trap efficiency of reservoirs or the portion of total sediment that the sediment sampler catches.

Variables used and regression results—The results of seven studies relating sediment yield from watersheds to its causes are summarized in Table 1. The equations were adjusted so that the regression results could all be compared: If sediment was expressed per unit area, for example, tons per square mile, then the log of area was added to both

TABLE 1 – *Variables used and regression coefficients determined in studies of total sediment yield from watersheds*[a]

Study number[b]	Area	Watershed constants			Watershed condition	Hydrologic events		Measuring device		Sedimentation period
		Physiography	Geology soils	Channel condition		Intensity	Amount	Reservoir	Sediment sample	
(1)	1.1	0.3–0.6	...	0.4	2.0	1.6	0.4	√[c]	...	Yearly
(2)	0.6	...	0.2	0.3	1.3	1.7	...	√	...	Single storm
(3)	0.8	...	...	...	1.1	...	...	0.4	...	Period
(4)	0.9	...	...	...	1.0	0.6	...	√	√	Period
(5)	1.0	0.1	...	...	0.7	0.1–3.1	1.9	√	...	Period
(6)	1.1	0.4	0.5	1.0	0.1–0.9	1.7	1.2	...	√	Period
(7)	0.8	...	...	...	0.2	...	0.9	0.5	...	Period

[a] Values in the table are the regression coefficients b in equations: Log sediment yield $= k + b_1 \log x_1 + b_2 \log x_2$, etc., where x_1, x_2, etc. are watershed variables, area physiography, etc.

[b] References: (1) *Anderson* [1949], (2) *Anderson* and *Trobitz* [1949], (3) *Gottschalk* and *Brune* [1950], (4) Glymph, Heinemann and Kohler, unpub., see *Glymph* [1954], (5) Kohler, unpub., see *Glymph* [1954], (6) *Anderson* [1954], (7) *Flaxman* and *Hobba* [1955].

[c] Check marks or a quantity indicate kind of sediment measurement.

sides of the equations to convert the sediment to totals; variables with somewhat different definitions were generalized into the hydrologic intensity and amounts; and the variable 'age of reservoir' was left out of the reported results.

Thus, the results shown in Table 1 must be considered as a generalization of the variables used in the seven studies and the regression coefficients obtained from the analyses. One of these studies dealt with yearly sedimentation of reservoirs; another with sedimentation of reservoirs by a single storm. The other studies were of some periodic measure of sedimentation, average annual sedimentation or total for a period. When total sediment for a period was used, the studies included age of reservoir as a separate variable. Depending on the purpose of the study, somewhat different variables were used to represent each of the major groups: The hydrologic events, the watershed conditions, and the watershed constants.

The hydrologic events were represented by either rainfall or streamflow variables. In some of the studies, the hydrologic events were considered as varying only from watershed to watershed so that only mean annual sedimentation was estimated. In other studies both watershed-to-watershed and time variations were considered so that both mean sedimentation and frequency of sedimentation were estimated. It must be concluded that more short-period measurements of sedimentation would permit much better evaluation of sedimentation frequencies than has been made heretofore.

The variables used to express watershed conditions were of two kinds: The kind that setup land use or vegetation cover as index variables, and the kind that grouped land use and certain soil and slope characteristics into the single variable called 'estimated erosion.' Studies 3, 4, and 5 used estimated erosion as an index of watershed condition. Notice in Table 1 that reservoir sedimentation varied from the 0.7 to 1.1 power of this index. For the purpose of the studies which were to aid in reservoir design the integrated variable 'estimated erosion,' was adequate. For the purpose of evaluating land use or treatment effects, however, separation of the land use from the slope and soil effects would probably be more desirable. Such separations were attempted in the other studies. In Studies 1, 2, and 7 single variables were employed to represent land condition: 'Cover density' was used in Studies 1 and 2, and 'land subject to erosion' in Study 7. In Study 6, four variables of land condition were used: Area of bare cultivation, area of other cultivation, areas of forest recently cutover, and area of roads. All the studies indicate that from existing or readily determinable data analyses can be made which will evaluate the effects of land use on sedimentation.

Among the watershed constants, area was the only one used in all seven studies. Sedimentation varied from the 0.6 to the 1.1 power of the area of the watershed. In these studies 'area' can well be called the devil's own variable. Almost every watershed characteristic is correlated with area. So every characteristic that is left out as a separate variable is in part hidden in 'area'. Big watersheds are not like little watersheds and the differences may be disguised in the term area. Therefore, it is dangerous to ascribe physical significances to the regression coefficient of the area variable. For example, if the regression coefficient were 0.7, it is doubtful if the deviation from 1.0, that

is, 0.8 represents erosion deposited enroute; if the regression coefficients were 1.1, it is equally doubtful that the deviation from 1.0 represents main channel scour.

As for the other watershed variables, these serve mostly to prevent confounding effects and point to the sources of sediment. Other variables include the physiography variables: *Horton's* [1945] channel bifurcation, slope, and length ratios, and land slope. Soil and geology variables have been represented by physical characteristics of the surface soil particles and by bare rock areas; channel conditions have been represented by area of main channel and length of eroding channel banks.

Now, to summarize briefly the salient feature of each analysis listed in Table 1:

Study 1: Yearly reservoir sedimentation measurements were available for analysis. Relationships found between sedimentation and peak discharges, rainfall, and cover density made possible estimation of sedimentation frequency and long-term mean sedimentation for various cover conditions.

Study 2: Sedimentation from a 100-year storm supplied useful criteria for design of reservoirs and debris basins. The variation of sedimentation with land cover condition during a major storm was evaluated.

Study 3: Simplification of analysis was achieved by comparing sediment yield with estimated erosion of the land. This, together with the inclusion of a measure of trap efficiency of the reservoirs, contributed to the predictive value of the results.

Study 4: A means was found for combining reservoir deposition and sediment sampling results in the same analysis. Reservoir deposition was corrected for trap efficiency before being used. This permitted data from more watersheds to be included in the analyses.

Study 5: Measures of the hydrologic events were used; number of rainstorms and rainfall above a minimum intensity added to predictive value.

Study 6: Results from a study of 33 watersheds were applied to a study of 17 of the watersheds for which additional information was available (the Corps of Engineers measurement of eroding main channel banks). The result was an improvement in the predictive value.

Study 7: This study applied the techniques of earlier studies to highly variable watersheds in the Pacific Northwest.

Uses of the regression results—The usefulness of these studies for predicting sediment yield from other similar watersheds is indicated by a comparison of actual sedimentation with that computed from the regression results. For most watersheds the computed values were within 25 pct of the actual in all except Study 7. Sediment estimates of this accuracy can be useful in designing reservoirs.

Sediment sources in a watershed may be located and evaluated by using the regression results. For example, application of the results of Study 6 yielded separation of the sources of sediment in the forest zone into ten hazard classes. Average annual sediment ranged from as little as 12 to as much as 600 tons per acre.

Another use of the regression is to estimate the effects of land use on sedimentation. It may be inferred that land use practices that change the amount of estimated erosion or the cover density can be evaluated by substituting that change in the regression equations. Where several land use variables are included in the analysis, the effects of each, as well as the total effect, can be evaluated. For example, in Study 6 the future sedimentation with full use of the forest lands was estimated to become three times the present; some 80 pct of the predicted increase in sedimentation was attributed to road development and only 20 pct to logging effects exclusive of logging roads.

Discussion—Regression analyses can be improved by using more care in the selection of watersheds, variables, data, and error criteria.

Watersheds selected for study are too often all those available. However, when we do have a choice, we should choose watersheds with wide diversity in those variables which we wish to evaluate. We should include all combinations of high and low. If curvilinearity is to be evaluated, then intermediate values of the variables will be needed. Ideally, the watersheds should be similar in all characteristics except those to be included as variables. Separating the watersheds into similar groups and analyzing by the method of covariance seems the next logical elaboration of regression analysis.

The choice of variables depends on the problem to be solved, the physical processes which are most important in sedimentation in the particular area, and the available information. Neglected variables are not really neglected; they hide in other variables and distort the relationships found. One source of neglected variables which deserves special discussion is the so-called non-significant variable.

Frequently, in the past, variables have been

dropped "because they were non-significant." The arbitrary choice, say the five per cent level, for this decision is statistical nonsense. Why we should choose to drop a measure which is unbiased, small, but differing from zero, and substitute the biased value of zero is not clear.

The statisticians do not suggest that we make any such arbitrary decision at the five per cent level; they tell us we must decide on the basis of the risks we are willing to take of (1) retaining a variable whose apparent effects are really due to chance and (2) dropping a variable with real effects. The 'real effect' of a variable which is worthwhile retaining in analyses relating sediment yield to watershed variables is one which would affect the results, most importantly affect the partial effects of the other variables. The added possibility that the several small effects may add up to an important effect makes dropping of individual variables risky. What is the value, then, of a test of significance? Since significance is based on the ratio of the effect of a variable to the error or variability in the effect, a non-significant result suggests: The variable is being measured with too much error, the function is wrong, or there was not enough range in the data to evaluate the effect properly.

Errors in variables, whether due to failure of the variable as an index or to the wrong function, introduce a bias in the effects being evaluated. The bias is always toward zero effect and depends intimately upon the range in the variable. The magnitude of this bias can be illustrated by introducing an artificial error in the data. A simple test of this kind showed that if the error in the variable was ten per cent of the range in the variable, the regression was only four per cent low; if the error was 20 pct, the regression was 14 pct low; if the error was 40 pct of the range, the regression coefficient was 39 pct low. It must not be thought that the errors in variables are the errors of measurement alone; rather the error is primarily the degree of failure of the variable to index the whole physical situation causing sedimentation. It is concluded, then, that we should seek improvement in the index relations of variables and extension of the range of variables. We should not use the test of significance as an excuse to drop variables which express physical effects that we expect to be important.

The more we know of basic physical processes, physiography, soils, and land use, the better variables we will devise and the greater will be their significance; but more important, the better will be our measure of their true average effect.

Conclusion—Some very useful results have been obtained from studies relating sediment yield to watershed variables. Sedimentation of new reservoirs can be predicted; the sources of sediment can be located, and sediment prevention can be evaluated. We can look to even better results as we put into these analyses greater knowledge of the processes of sedimentation and better variables.

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Needed Research in Sedimentation

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Abstract—All phases of sedimentation research are greatly in need of expanded research. The growing small watershed program will require greater concentration on fundamental mechanics of sedimentation processes rather than generalities. Particular attention is suggested for research in channel stability and new measurement techniques.

It is difficult to imagine a recognized field of science which is broader and more complex than sedimentation. Even if we restrict our sights to those of this symposium, Watershed Erosion and Sediment Yields, the breadth of problems is immense. In the processes between erosion and deposition, soil particles are acted upon by many forces which are difficult to measure and evaluate. Sediment rates are highly variable because the many interrelated factors themselves vary in time and space. Because of the breadth of variables, many sciences must participate if research progress is to be made, and this indicates the necessity of a team approach.

The purpose of research is to learn cause and effect so that with this knowledge we may predict behavior in our planning, and so that we may control or modify events to our advantage. Our present understanding of the mechanics of sedimentation is infinitesimal as compared with what is yet to be learned. This is not to discredit the fine work which has been done, because this is a new science. At present we are still in a descriptive and qualitative stage, and tremendous research opportunities lie ahead. We are still heavily dependent upon "sound judgment and experience." This infers that the mind can integrate numerous complex variables, but only approximately, because we cannot, with exactness, describe the models or write the equations.

It would be fine if scientists could follow their curiosity through this sedimentation maze. But the facts of life are otherwise. There is very little research for curiosity's sake in this country today. Almost all of it is related to specific needs for answers to pressing problems confronting us. This is true in sedimentation as well as in other fields.

The largest action program on the horizon today, and the one which we feel is going to affect the future need for sedimentation research, is the small-watershed program of the U. S. Department of Agriculture. This program will require fundamental studies in sedimentation. In the large reservoir program, large areas were involved which generally cut across climatic and physiographic boundaries. This smoothed out many of the variabilities in sedimentation rates. But sedimentation is highly variable, and when we become concerned with small areas, this becomes of more direct concern. Differences of several hundred per cent occur within a short distance. Tolerances for error will become smaller. There will no longer be the many thousand acre feet or several centuries in which to bury our errors. Designers cannot limit their thinking to 'virgin' rates of sediment yield or transport, but will be faced with numerous upsetting influences of man. Each of the thousands of expected structures will set up new counter forces which nature will try to re-establish in balance. Qualitative judgments as to the general effects of these programs, will involve large errors. Very likely, too, the main concern is not going to be in the predicting of sediment yield in order that an adequate sediment pool be reserved. The major problems will concern stability of channels. These will be so diverse and so numerous, that generalities will not suffice. Sedimentation research must develop sound theory and evaluate this with intensive field studies.

Where do we stand at present in our understanding of the mechanics of sedimentation? A logical place to start is with the basic erosion process on the land, where detached soil particles become the material with which we deal. In the basic erosion process investigators have identified rainfall, soil, length of slope, degree of slope, and kind of vegetation as the primary factors involved. There are other forces causing erosion, of course, than rainfall, but this is the most important source of the energy. In any case it is the most commonplace, and other forces are even more obscure. At present we do not know how to evaluate rainfall in the erosion process. Obviously rainfall is an important and highly variable factor. One equation in use for estimating rates of sheet erosion introduces precipitation as the maximum 30-minute rainfall at a two-year frequency. Another investigation found that use of precipitation in inches per year

improved the correlation in an equation predicting sediment yield. These are obviously over-simplified measures of the energy and influence of rainfall, and can be thought of as having 'index' value. Recently a committee of experts reviewing and re-evaluating the various factors used in soil loss equations indicated that our present knowledge of the influence of rainfall does not justify its insertion in erosion equations. Here then is an important research opportunity for someone. Evaluate the influence of rainfall in its broadest sense on the mechanics of erosion. When this is done we can utilize our long-time rainfall records to extend short and limited erosion data.

What about the other variables such as soil type which were mentioned as having a bearing on erosion? We know that there are thousands of different soils, with widely varying characteristics including their resistance to erosion. Also, soils are not static in their characteristics, but change with moisture content, season, degree of erosion, and many other factors. How do we measure inherent erodibility or detachability of soil? There is no single measure. There are laboratory tests which give relative values of aggregate stability, etc. But we do not have a satisfactory technique for measuring the inherent and changing character of the soil as it reacts to the influences of rainfall and other factors in relation to erosion. Regarding the factors of degree and length of slope, we have a little better information, but not nearly enough.

Perhaps the least tangible factor in the whole equation of soil loss is the effect of vegetation, since this involves difficult and qualitative measures of management. There are numerous vegetal covers, tillage and other practices for which we have no experimental data.

There certainly is great opportunity for research in this area, but this is just the beginning of the whole sedimentation process. We know in a general way that much of the displaced soil does not go far. A large portion of the material is deposited at the foot of slopes in fields, along fence rows, etc., prior to getting into a defined channel. Here is a whole segment of the sediment problem which has received little attention. It would seem that some day an attack must be made on this intermediate segment. This will no doubt be complex.

Gullies as a source of sediment is discussed in an another paper on this symposium. Here too, much research remains to be accomplished. We believe that present estimates of this sediment source are based on observation and by such means as comparing successive aerial photographs which may be available. Here too, past studies have been too superficial. *Peterson*, [1950] has outlined needed research relative to gullies, and with particular reference to the West where they are the most important feature. He points out the interrelations of parent material, climate, and vegetation. He states that "prosecution of this research will necessitate detailed inquiry into the many interrelated aspects of erosion." In this we feel that Peterson has hit at the heart of the problem. Every gully is different from every other gully. We can not classify gullies. The lowest common denominators are the physical forces and resistances of nature and man. In addition to reading the maximum value out of geology and history, detailed instrumentation is required at diverse sites where all of the pertinent physical factors can be continuously measured and correlated.

Sediment transport in channels has been the focus of considerable research by hydraulic engineers and others. This is where the most critical research needs are today. It is in this phase of sedimentation where the effects of the watershed programs will change the natural regimen. Increases and decreases in runoff, sediment load, and regulation of streamflow will set in motion new cycles of aggradation and degradation which should be accurately anticipated. Sediment transport problems are not confined to natural channels. We have, for example, the age-old problem of design and maintenance of irrigation canals where sediment is usually present.

Present sediment transport formulas are based almost entirely on numerous flume studies, some of which go back to the last century. Application of these to field conditions has led to serious errors in computing the transport capacity and the design of stable channels. Perhaps there are shortcomings in our basic theory, and it appears that the matter of cohesion of soil particles is as yet unevaluated. Bank vegetation is another factor which is difficult to deal with. In any case, workers in this field at the present time generally approach design problems with several theoretical formulas and then apply experience, judgment, and safety factors. This evidence of lack of satisfactory theory must no doubt be met this way at present, but ultimately we must improve on judgment with sound theory and evaluated factors to fit field conditions.

It seems to us that the most productive approach for future research will be to establish outdoor laboratories by instrumenting and observing con-

ditions on full-scale reaches of natural rivers and canals. The traditional laboratory studies will have a role in this picture by developing interpolations between field conditions and with studies of single variables under controlled conditions.

From sediment transport in channels we move on to a consideration of sediment deposition primarily as it is concerned with deposition in reservoirs. Again we are faced with immensely complex conditions which defy analysis at present. Yet high values are at stake. This combination will undoubtedly lead to greater attention in the future.

Perhaps the most troublesome aspect is the deposition in the headwaters of reservoirs. Here sediment is most likely to affect values of lands and encroach upon operating storage. *Bondurant* [1955] reveals many departures from the idealized pattern of deposition. Yet we are just on the threshold of these investigations, and most studies have been of a casual or reconnaissance nature. We must close the gap with itensified research including comprehensive measurements of all the variables believed to play a part.

Other problems associated with deposition in reservoirs are trap efficiency and sediment density. Trap efficiency, the ratio of the sediment stored to that entering the reservoir is of primary importance. Little information is presently available for the flood-water retarding type structures coming into widespread use. Studies of these were initiated last year and it is hoped that they can be expanded.

For the same reasons it is important to be able to predict the density of deposited sediment so that the ultimate sediment storage space may be predicted from the weight of sediment entering the pool and estimated trap efficiency. Refinement of density determinations has been seriously hampered in the past by lack of adequate measurements. A promising device is now under development by the Bureau of Reclamation under sponsorship of the Sedimentation Subcommittee, Inter-Agency Committee on Water Resources. This should open the way for expanded research in this field based on improved measurements of actual deposits.

Finally we wish to comment briefly on the need for further research on improved techniques and equipment in the field of sedimentation. This has represented a principle obstacle, although notable progress has been made in a number of instances. For example, through the cooperative efforts of federal agencies an excellent selection of suspended sediment samplers has been developed. That group now proposes to initiate work on automatic devices for measuring sediment concentration. The Coshocton Runoff Sampler has made it possible to take much of the labor and expense out of measuring soil loss from plots and small watersheds. These developments are important because they make possible larger additions to our data with limited resources.

If we might make a final and long-shot estimate for needed sedimentation research it is in this field of new techniques. The next major breakthrough may come in our ability to develop tracer techniques useful in sedimentation research. Other branches of science are employing radioactive and other tagged material to follow complex relationships. Why should we not be able to adopt these techniques?

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The Magnification Caused by Partial Resonance of the Foundation of a Ground Vibration Detector

G. N. Bycroft

Abstract—This note is intended to indicate the values of magnification and phase shift arising in a ground vibration detector due to partial resonance of the instrument on the ground. Results from a previous paper by the author are used to derive curves of magnification and phase shift. It is shown, by an example, that a typical geophone will give results grossly in error when the frequencies of the measured vibrations are high.

Introduction—The typical inertia-type pick-up for measuring ground vibration, such as a geophone or seismograph, has associated with it two mass-spring systems. The first system is that of the sensing mass and its constraint. The effect of the dynamics of this system is well known and need not be further mentioned. The second system consists of the mass of the pick-up frame and foundation and the elastic constraint of the ground. The mass of the pick-up will change the ground motion at the measuring point from what it was if the pick-up were not there. In certain circumstances magnification or attenuation of the ground motion together with a phase shift will be significant.

This note considers the value of this magnification when the pick-up sits on a homogeneous elastic half space and is detecting sinusoidal waves of wave length large compared to the diameter of the base of the pick-up.

In order to solve this system it is necessary to know the mechanical impedance of a rigid plate attached to the surface of an elastic half space. This, of course, is the main part of the problem and it has been considered by the author [*Bycroft*, 1956]. It is shown in this reference that the displacement of a weightless rigid circular plate attached to a semi-infinite elastic space and excited by a vertical sinusoidal force may be expressed by two functions of frequency f_1 and f_2.

These functions correspond to the in-phase and out-of-phase components of the displacement. The following notation is used and only a circular base is considered:

λ, μ = Lamé's elastic constants of the material

ρ = density of the material

p = angular frequency of impressed force on the plate

$\rho p^2/(\lambda + 2\mu) = k^2$, $\rho p^2/\mu = k^2$, that is $2\pi/h$ is the wave length of the compressional wave and $2\pi/k$ that of the shear wave

r_0 = radius of base plate

P = amplitude of exciting force

kr_0 = a_0, that is, effectively a non-dimensional frequency factor

h/k = τ, that is, ratio of the wavelengths and is nominally $\frac{1}{3}$,

f_1, f_2 are functions of a_0 and τ and have been shown to be such that the displacement of the weightless plate excited by a force $R_e Pe^{ipt}$ is given by

$$U = R_e \frac{-Pe^{ipt}}{\mu r_0} (f_1 + if_2)$$

These functions are shown in Figure 1.

When the frequency or a_0 is small, the plate on the elastic medium acts as a weightless undamped spring and the function f_1 corresponds to the static stiffness of the system. However, as the frequency is increased, elastic wave motion is generated in the medium and the inertia of the medium decreases the function f_1. Waves are now being propagated outwards and not returning. This energy loss is shown by the rise in value of the radiation component f_2. The actual amplitude of the vibration is proportional to $\sqrt{f_1^2 + f_2^2}$ This characteristic droops with increasing frequency and exhibits no resonance. The situation is similar to that of radio propagation from an aerial in free space.

If mass is added to the plate we have then a mass on a damped spring, the stiffness and damping of which are functions of frequency. In this case damped resonance can occur.

The particular application to a geophone will now be considered. If m_0 = mass of instrument case and its foundation sitting on a base of radius r_0, let $b = m_0/\rho r_0^3$, that is, a non-dimensional mass-factor.

Let the displacement of the ground at the

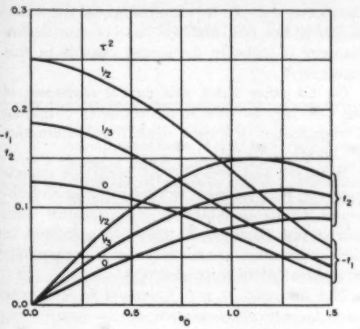

FIG. 1 – Relation between a_0 and $-f_1$, f_2

measuring point, when unloaded by the instrument, be the real part of Be^{ipt} and let the force between the ground and the instrument when the instrument is in place be $Pe^{ip(t+\epsilon)}$. The motion of the instrument will consist of two displacements, the original undisturbed displacement Be^{ipt} and the displacement caused by the force $Pe^{ip(t+\epsilon)}$ under the instrument. The system is linear and the displacements may be added. The displacement caused by the force $Pe^{ip(t+\epsilon)}$ is given by

$$U_1 = \frac{-Pe^{ip(t+\epsilon)}}{\mu r_0}(f_1 + if_2) \tag{1}$$

Addition of the two displacements gives the displacement of the instrument

$$U_2 = Be^{ipt} - \frac{Pe^{ip(t+\epsilon)}}{\mu r_0}(f_1 + if_2) \tag{2}$$

Equate the force acting on the mass m_0 to its mass acceleration, and

$$-m_0 p^2 e^{ipt}\left[B - \frac{Pe^{ip\epsilon}}{\mu r_0}(f_1 + if_2)\right] = -Pe^{ip(t+\epsilon)} \tag{3}$$

The real and imaginary parts of this equation yield

$$\cos p\epsilon = \frac{m_0 p^2}{\mu r_0}\left[\frac{B\mu r_0}{P} - f_1 \cos p\epsilon + f_2 \sin p\epsilon\right] \tag{4}$$

$$\sin p\epsilon = \frac{-m_0 p^2}{\mu r_0}[f_1 \sin p\epsilon + f_2 \cos p\epsilon] \tag{5}$$

Elimination of the phase ϵ gives

$$P^2 = \frac{m_0^2 p^4 B^2}{\left[\left(1 + \frac{m_0 p^2 f_1}{\mu r_0}\right)^2 + \frac{m_0^2 p^4 f_2^2}{\mu^2 r_0^2}\right]} \tag{6}$$

Finally, we obtain for the magnitude of the loaded ground displacement

$$A = |U_2| = \frac{B}{[(1 + ba_0^2 f_1)^2 + (ba_0^2 f_2)^2]^{\frac{1}{2}}} \tag{7}$$

The phase angle ϕ between the undisturbed displacement and the new displacement is given by

$$\tan \phi = \frac{ba_0^2 f_2}{(1 + ba_0^2 f_1)} \tag{8}$$

From (7) we define the magnification factor as

$$M = \frac{1}{[(1 + ba_0^2 f_1)^2 + (ba_0^2 f_2)^2]^{\frac{1}{2}}} \tag{9}$$

The functions f_1 and f_2 are quoted from the author's earlier paper and are shown in Figure 1. Figures 2 and 3 show the magnification factor M and the phase angle ϕ, as function of the non-dimensional frequency factor a_0 and mass factor b.

A typical example may be quoted to indicate the significance of these results. Consider a geophone sitting on a base of four inches diameter and of seven pounds weight. If the ground den-

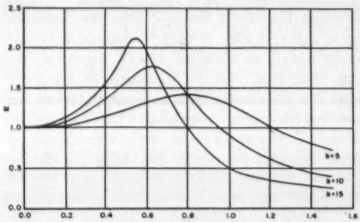

FIG. 2 – Relation between a_0 and M, $\tau^2 = \frac{1}{3}$

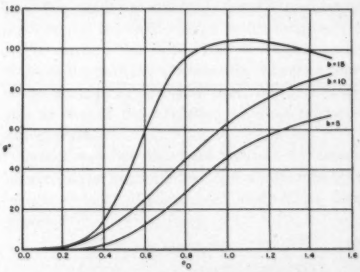

FIG. 3 – Relation between a_0 and ϕ, $\tau^2 = \frac{1}{3}$

sity is assumed to be one hundred pounds per cubic foot then

$$b = \frac{m_0}{\rho r_0^3} = \frac{7}{100 \times 0.167^3} \simeq 15$$

If the shear wave velocity is one thousand feet a second and the instrument is measuring a frequency of five hundred cycles per second, then

$$a_0 = kr_0 = \frac{500 \times 2\pi \times 0.167}{1000} = 0.52$$

The curves in Figure 2 show that the apparent displacement is twice the correct value. Figure 3 indicates a phase difference of 32°.

Conclusions—It may be seen from the example quoted that the mass of a ground measuring instrument will substantially alter the motion at the pick-up point and radically alter the shape of any complex train of waves it is receiving both by amplitude and phase changes. The greater the value of b for the instrument placement the greater will be the maximum magnification. This distortion may be avoided by decreasing the b value of the instrument. Increasing the base area is probably the easiest way of achieving this. Although increasing the base area also increases the a_0 value, it may be seen from the curves that better fidelity is obtained overall. However, the base area must not be increased to the stage when its dimensions become comparable to the wavelengths being measured. This limitation, which will certainly arise with high frequency waves, can only be met by decreasing the mass of the pick-up unit. In the example quoted the wavelength is two feet and the base of four inches diameter is probably the largest possible in this case.

On the other hand, this partial resonance of the base may be used to advantage in obtaining a magnification of a weak signal if the parameters are chosen correctly.

Washburn and *Wiley* [1941] performed experiments on the placement of a seismometer and obtained results qualitatively in accordance with this theory. However, as the wave velocities in their experiments are not stated it is not possible to make a quantitative comparison.

The functions f_1 and f_2 quoted in this note refer to vertical translation of the instrument. The same paper gives results for the other degrees of freedom of the instrument and the reader is referred to the reference for the relevant functions.

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Radiative Transfer in the Earth's Mantle*

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Abstract—The equation governing the transfer of heat in non-opaque media is derived and reduced to a form suitable for calculation. The optical absorption coefficients of minerals are estimated to be 10 cm^{-1} to 30 cm^{-1} under surface conditions, but they rise to much higher values at high temperatures because of an increase of electrical conductivity with temperature. Hence radiative transfer will be most effective in the outermost 600 km of the Earth; at these depths the effective thermal conductivity may be considerably increased by radiative transfer. The presence of an outermost shell having a high conductivity may increase the heat lost from the Earth in geologic time by a factor of two over previous estimates.

Introduction—The contribution of radiation to the transfer of heat in non-opaque materials has been the subject of extensive discussion in the literature of glass technology [see *Preston*, 1956, for further references]. It is estimated that at 1200°C the apparent conductivity of glass is about 50 times as large as the ordinary conductivity at room temperature [*Kellett*, 1952].

A similar effect was discovered by *McQuarrie* [1954a] during the measurement of the thermal conductivity of ceramics at high temperature. He found that the apparent conductivity of BeO, MgO, and Al_2O_3 increased with temperature between 1500° and 1800°C, contrary to theoretical prediction. The measurement of thermal conductivity at high temperature involves formidable experimental difficulty, and the law of increase of conductivity with temperature is not well-defined by McQuarrie's work. But the fact that the conductivity does increase is beyond doubt, and *McQuarrie* [1954b] attributed the phenomenon to radiative transfer.

Radiative transfer has largely escaped the attention of geophysicists. *Birch* and *Clark* [1940] recognized its possible importance in the Earth, but their remark seems to have been overlooked in subsequent discussions of terrestrial temperature. Thin slices of rock transmit radiation readily, as is known to any petrographer. Although thick specimens appear opaque, radiative transfer is still possible by absorption and reemission. The amount of energy transferred by radiation is, to a first approximation, proportional to the cube of the absolute temperature. Although the effect of radiation may be small at room temperature, it may become more important than ordinary conduction above 1000°K.

Several geophysicists have suspected that the thermal conductivity in the mantle is considerably higher than is indicated by measurements on rocks at ordinary temperatures and pressures. *Slichter* [1941] assumed high conductivities at depth in calculating temperature-depth curves, but he did not attempt to justify his assumption. *Uffen* [1954] suggested that the lattice conductivity of silicates would be greatly increased by pressure. It is suggested here that radiative transfer provides an additional mechanism leading to high effective thermal conductivity in the mantle.

Theory—The theory of the contribution of radiation to the transfer of heat has been discussed by several authors [*Van der Held*, 1952; *Kellett*, 1952; *Condon*, 1953; *Genzel*, 1953], but these treatments are subject to restrictive approximations which often are not explicitly stated. We shall therefore rederive the equation of heat transfer in non-opaque media, making only those approximations which are presumed to be valid in the Earth.

In a previous note on this subject [*Clark*, 1956], the treatment given by *Van der Held* [1952] was used. His solution is valid only if both the thermal gradient and the total change in the temperature of the medium are small. The numerical results of the earlier note are substantially correct because of the integration procedure used, but it is desirable to remove the restriction to small temperature changes.

Definitions—Let the total amount of energy between wave lengths λ and $\lambda + d\lambda$ emitted by a volume element dV_0 into solid angle $d\Omega$ in time dt be

$$E_\lambda d\lambda d\Omega dt dV_0 \qquad (1)$$

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Similarly, the total energy of monochromatic, unpolarized radiation in solid angle $d\Omega$ passing through a surface element dS_0 in time dt is

$$\cos\theta\, K_\lambda d\lambda d\Omega dt dS_0 \qquad (2)$$

where θ is the angle between the normal to the surface and the pencil of radiation. These equations define the monochromatic emissive power, E_λ, and the monochromatic intensity of radiation, K_λ. Consider a pencil of monochromatic radiation passing through the medium in the x direction. The intensity of radiation is $K_{\lambda 0}$ at $x = 0$. At the point x, the intensity is $K_{\lambda 0}e^{-\alpha_\lambda x}$ in an absorbing medium with no scattering centers and $K_{\lambda 0}e^{-\epsilon_\lambda x}$ in a non-absorbing medium with scattering centers. These relations define the absorption and scattering coefficients, α_λ and σ_λ. Let

$$\epsilon_\lambda = \alpha_\lambda + \sigma_\lambda ;$$

for want of a better term, ϵ_λ will be called the 'opacity' of the medium.

If n_λ is the refractive index, a fundamental law of heat radiation states that $E_\lambda/n_\lambda^2\alpha_\lambda$ is a universal function of λ and the temperature T [*Planck*, 1914]. We shall call this function $J(\lambda, T)$.

Approximations—Two measures of length affect problems of radiative transfer. The first is the physical size of the region under consideration, and the second is the mean free path of the radiation, which equals the reciprocal of the opacity. If the two are of the same order of magnitude, the boundaries of the region have a profound effect on the radiation in its interior, and the treatment of the problem becomes complicated. In the Earth, the mean free path will not exceed a few centimeters, and boundary effects will be neglected.

Only small departures from thermal equilibrium will be considered. More precisely, the fractional changes in the quantities T, J, ϵ_λ, etc., are assumed to be small in a distance ϵ_λ^{-1}. J and K_λ are assumed to be regular functions of position in the sense that each may be expanded in a convergent power series about any point in the region.

There is no lag between the radiation field and its sources; the radiation is then independent of $\partial T/\partial t$. Scattering is assumed to take place without change of wave length, and absorption, emission, and scattering are all assumed to be isotropic.

Derivation of the generalized conduction equation—In the following we omit most algebraic manipulations. These, although tedious, are straightforward.

The radiant energy at a point O between wave lengths λ and $\lambda + d\lambda$, due to emission and scattering at surrounding points, is

$$4\pi K_{\lambda 0} = \int_v [n_\lambda^2\alpha_\lambda J(\lambda, T) + \sigma_\lambda K_\lambda]\frac{e^{-\epsilon_\lambda r}}{r^2}dV \qquad (3)$$

[*Planck*, 1914], where the integration is over all space and the subscript o designates quantities evaluated at O. To obtain an expression for K_λ, we expand $J(\lambda, T)$ in a Taylor's series about O and assume α_λ, σ_λ, and ϵ_λ independent of position. The latter approximation is valid provided $\frac{\Delta\epsilon_\lambda}{\epsilon_\lambda} \ll 1$, etc. in the portion of the surroundings which contributes appreciably to the integral. Many of the terms in the expansion vanish in the integration, and we are left with

$$K_{\lambda o} - \int_v \sigma_\lambda K_\lambda \frac{e^{-\epsilon_\lambda r}}{4\pi r^2}dV = n_\lambda^2\alpha_\lambda\left[\frac{1}{\epsilon_\lambda}J_o(\lambda, T) + \frac{1}{3\epsilon_\lambda^3}\nabla_o^2 J(\lambda, T) + \cdots\right] \qquad (4)$$

The form of the right side of (4) suggests that K_λ be expanded in the series

$$K_\lambda = \sum_0^\infty c_i \nabla^{2i} J(\lambda, T) \qquad (5)$$

where the c_i are constants to be determined. Each term on the right of (5) may be expanded in a Taylor's series; substitution of the result in (4) gives, after integration

$$c_0 J_o(\lambda, T) + c_1\nabla_o^2 J(\lambda, T) + \cdots = \frac{n_\lambda^2\alpha_\lambda}{\epsilon_\lambda}\left[J_o(\lambda, T) + \frac{1}{3\epsilon_\lambda^2}\nabla_o^2 J(\lambda, T)\right] + \frac{\sigma_\lambda}{\epsilon_\lambda}[c_0 J_o(\lambda, T) + c_1\nabla_o^2 J(\lambda, T)] + \frac{\sigma_\lambda}{3\epsilon_\lambda^3}c_0\nabla_o^2 J(\lambda, T) + \cdots \qquad (6)$$

Collecting coefficients, we find

$$c_0 = n_\lambda^2,\ c_1 = n_\lambda^2/3\alpha_\lambda\epsilon_\lambda, \ldots \qquad (7)$$

We next calculate the normal component of the net flux of radiant energy, $\mathbf{F}$, through a surface element $d\mathbf{S}_o$. This is given by

$$\pi\mathbf{F}\cdot d\mathbf{S}_o = \int_\lambda\int_v [n_\lambda^2\alpha_\lambda J(\lambda, T) + \sigma_\lambda K_\lambda] \cdot \frac{e^{-\epsilon_\lambda r}}{r^2}\mathbf{r}\cdot d\mathbf{S}_o\, dV\, d\lambda \qquad (8)$$

where $\hat{\mathbf{r}}$ is a unit vector in the radial direction, and K_λ is given by (5) and (7). Again we use the device of expansion of $J(\lambda, T)$ about O, and find that most of the terms vanish in the integration. We are left with

$$\mathbf{F}\cdot d\mathbf{S}_o = \frac{4}{3}\int_\lambda \frac{n_\lambda^2}{\epsilon_\lambda}\nabla_o J(\lambda, T)\cdot d\mathbf{S}_o\, d\lambda + 4\int_\lambda n_\lambda^2\left(\frac{\sigma_\lambda}{9\alpha_\lambda \epsilon_\lambda^2}+\frac{1}{5\epsilon_\lambda^2}\right)\cdot\nabla_o(\nabla_o^2 J(\lambda, T))\cdot d\mathbf{S}_o\, d\lambda \quad (9)$$

Consider a region R (not necessarily infinitesimal) bounded by a surface S. It is not valid to treat $\mathbf{F}$ as constant throughout R, but it is assumed to be given by (9) at every point on S. We therefore drop the subscript o. Conservation of energy in R implies

$$\int_R\left(-A+\rho c\frac{\partial T}{\partial t}\right)dV = \int_s (K\nabla T+\mathbf{F})\cdot d\mathbf{S} \quad (10)$$

where A is the rate of heat generation per unit volume, K is the ordinary thermal conductivity, ρ the density, and c the specific heat. Application of the divergence theorem to (10) yields, by the usual argument

$$\rho c\frac{\partial T}{\partial t} = A+\nabla\cdot(K\nabla T+\mathbf{F}) \quad (11)$$

Since $J(\lambda, T)$ depends on position only through its dependence on T,

$$\nabla J(\nabla, T) = \frac{\partial J(\lambda, T)}{\partial T}\nabla T \quad (12a)$$

and

$$\nabla[\nabla^2 J(\lambda, T)] = \frac{\partial}{\partial T}[\nabla^2 J(\lambda, T)]\nabla T \quad (12b)$$

In the Earth a further simplification is possible. $\nabla^2 J(\lambda, T)$ is of the order $(\partial J/\partial T)\nabla^2 T$. But $\nabla^2 T$ is of the order T/a^2, where a is the radius of the Earth. Hence only the first term on the right of (9) need be retained, and we have finally

$$\rho c\frac{\partial T}{\partial t} = A+\nabla\cdot\left(K+\frac{4}{3}\int_0^\infty \frac{n^2(\lambda, T)}{\epsilon(\lambda, T)}\frac{\partial J(\lambda, T)}{\partial T}d\lambda\right)\nabla T \quad (13)$$

The effective conductivity—We define the effective conductivity C to be the sum of the ordinary conductivity, K, and the radiative conductivity, C_r.

$$C = K+C_r = K+\frac{4}{3}\int_0^\infty \frac{n^2(\lambda, T)}{\epsilon(\lambda, T)}\frac{\partial J(\lambda, T)}{\partial T}d\lambda \quad (14)$$

$$J(\lambda, T) = \frac{2\pi c^2 h}{\lambda^5(e^{hc/\lambda kT}-1)},$$

h is Planck's constant, k is Boltzmann's constant, and c is the velocity of light. We now assume that at any temperature n^2/ϵ may be replace by a piecewise constant function of λ. Eq. (14) then becomes

$$C = K+\frac{4}{3}T^3\Sigma_i \frac{n_i^2(T)}{\epsilon_i(T)}\int_{x(\lambda_{i-1}, T)}^{x(\lambda_i, T)}\frac{2\pi k^4}{h^3c^2}\frac{x^4e^x\,dx}{(e^x-1)^2} \quad (15)$$

where $x = hc/\lambda kT$ and $n_i^2(T)/\epsilon_i(T)$ is the mean value of $n^2(\lambda, T)/\epsilon(\lambda, T)$ in the spectral interval between λ_{i-1} and λ_i at temperature T.

Values of the integral in (15) are given in Table 1. At low temperatures a considerable portion of the energy is at long wave lengths, but at these temperatures the total contribution of radiation is small. Up to 3000°K, only a small error is in-

TABLE 1 — *Values of* $\dfrac{\int_{x(\lambda_2)}^{x(\lambda_1)}\frac{x^4e^x dx}{(e^x-1)^2}}{\int_0^\infty \frac{x^4e^x dx}{(e^x-1)^2}}$.

T	Spectral range, microns											
	∞–5	5–4	4–3	3–2½	2½–2	2–1½	1½–1	1–0.8	0.8–0.7	0.7–0.6	0.6–0.5	0.5–0
°K												
1000	0.208	0.127	0.223	0.147	0.149	0.112	0.031	0.001	...	...	...	...
2000	0.033	0.029	0.072	0.074	0.127	0.223	0.297	0.094	0.029	0.017	0.004	0.002
3000	0.011	0.009	0.024	0.031	0.059	0.129	0.295	0.177	0.092	0.079	0.061	0.033
4000	0.006	0.004	0.011	0.013	0.029	0.072	0.201	0.169	0.111	0.120	0.120	0.146
5000	0.004	0.004	0.006	0.007	0.015	0.042	0.133	0.127	0.098	0.125	0.147	0.295

* $\dfrac{2\pi k^4}{h^3c^2}\int_0^\infty \frac{x^4e^x dx}{(e^x-1)^2} = 5.42\times 10^{-12}$ cal/cm²sec(°C)⁴

troduced by neglecting radiation outside of the range 0.5 to 5 microns.

The absorption coefficient—The mechanisms by which solids absorb radiation may conveniently be classified into four types. (1) Absorption by the excitation of lattice vibrations (lattice absorption). (2) Absorption by the excitation of electrons in atoms or near points where the lattice is distorted (exciton absorption). (3) Absorption by the excitation of electrons into the conduction band of the crystal (electronic absorption). (4) Absorption by mobile charge carriers.

Lattice absorption causes the infrared absorption spectrum; in silicates at ordinary temperatures and pressures the main absorption peaks are at wave lengths greater than five microns [*Launer*, 1952]. Electronic absorption takes place in the ultraviolet, at wave lengths less than 0.4 micron in peridot [*Runcorn* and *Toser*, 1955, p. 101; there is a misprint in the reference; the ultraviolet absorption edge is given as 0.3 micron]. The optical 'pass band' of crystals lies between the region of lattice absorption and the ultraviolet absorption edge.

Absorption within the pass band—Exciton absorption is partially responsible for color in silicates containing transition elements. In glasses, the Fe^{++} ion produces a weak absorption peak at about 1.1 microns [*Weyl*, 1951], and a similar peak occurs at about the same wave length in iron-bearing crystalline silicates [*Coblentz*, 1906]. The position of this peak depends on the coordination number of the iron, and the amount of absorption is highly sensitive to composition and to the valence of the iron.

Accurate data on the absorption coefficients of minerals are almost non-existent; one reason is that the results of transmission experiments depend on both reflection and absorption. Allowance for specular reflection from a smooth surface is readily made, either by direct experiment or from theory. But it is nearly impossible to correct for diffuse reflection from a rough surface unless measurements have been made on samples of several thicknesses, and diffuse reflection may be far stronger than specular reflection. No quantitative information about the absorption coefficient can be obtained from the considerable amount of data available on the transmission of thin films of powdered material, because large and uncertain corrections for diffuse reflection and scattering within the sample are required.

In the course of this study, exploratory measurements of the opacities of several basic rocks were made. The transmission was measured with a red-sensitive phototube, which responds to a range of frequencies about 0.4 micron wide with its center at about 0.8 micron. Samples were in the form of plates 0.8 to 2.3 mm thick, with a surface area of about 1.5 sq in. The use of slices of several thicknesses from the same rock enabled a correction to be made for reflection.

The most serious obstacle encountered in the measurements arose from the difficulty in obtaining samples of basic rocks which are free from weathering. Cloudy patches were present in all of the specimens used in this work, and in many cases visual examination suggested that perhaps half of the opacity of the specimen resulted from scattering by fine-grained alteration products. These are not expected to be present in the mantle, where the minerals are probably in chemical equilibrium with their environment.

These measurements were rough, and little would be gained by presenting them in detail. Of the types of rock investigated (dunite, eclogite, peridotite, and gabbro), none showed values of ϵ greater than 30 cm^{-1}. The lowest values, found for the freshest dunites, were near 10 cm^{-1}.

Values of the absorption coefficients of a few anhydrous silicates, estimated from transmission data given by *Coblentz* [1906], are given in Table 2. These values are too high, because the surfaces of Coblentz's specimens were not optically smooth. The effect of surface roughness is exaggerated in very thin specimens; this may in part account for the high apparent absorption of the feldspars.

Effect of temperature and pressure on absorption in the pass band—The amount of absorption in the pass band will increase as the temperature rises. This is due in part to increasing absorption from exciton processes, but measurements of the opacities of dunite and eclogite (the only rocks showing reversible temperature coefficients of those tried) at 0.8 micron indicate that the opacity rises by only about 10 to 20 pct between 0° and 500°C. The small size of this change is perhaps spurious, for scattering within the sample, which is likely to be insensitive to temperature, may have contributed appreciably to the observed opacity.

A much larger effect arises because at higher temperatures silicates show appreciable electrical conductivity. The classical relation between electrical conductivity and optical absorption is

TABLE 2 – *Absorption coefficients of a few anhydrous silicates calculated from data given by Coblentz [1906]*

Mineral	Thickness	Spectral range, microns					
		5–4	4–3	3–2½	2½–2	2–1½	1½–1
	mm	cm^{-1}	cm^{-1}	cm^{-1}	cm^{-1}	cm^{-1}	cm^{-1}
Orthoclase	0.07	58	76	92	103	128	152
Albite	0.14	59	42	50	49	60	
Garnet	3.25	13	5	9	23	22	12
Bronzite	1	15	13	12	18	23	18

$\alpha = 120\pi\sigma/n$, where the electrical conductivity σ is in ohm^{-1} cm^{-1}, and α is in cm^{-1} [*Menzel*, 1953, p. 312]. This relation is independent of the conduction mechanism, but both the electrical conductivity and the absorption arising from this effect must be evaluated at the same frequency. Measurements of the electrical conductivity of silicates and determinations of the conductivity in the Earth have been made at frequencies much lower than the optical frequencies considered here.

A simple relation expressing the dependence of electrical conductivity on frequency is $\sigma(\omega) = \sigma(0)/(1 + (\omega\tau)^2)$, where ω is the frequency and τ the collision time [*Fan*, 1955]. But for a semiconductor [*Seitz*, 1940, p. 536]

$$\sigma = \sigma_0 e^{-E/2kT} = \frac{n_0 e^2}{m^*}\tau$$

and [*Peierls*, 1955, p. 199]

$$n_0 = 2\left(\frac{2\pi m^* kT}{h^2}\right)^{\frac{3}{2}} e^{-E/2kT}$$

where e is the electronic charge, n_0 is the total number of excited charge carriers, m^* is the effective mass of the charge carriers, and E is the width of the energy gap of the crystal. For several silicates σ_0 is of the order of 1 ohm^{-1} cm^{-1}; setting T equal to 1000°K and taking m^* equal to the electronic mass, we find $\tau \approx 10^{-17}$ sec. Since $\omega \approx 10^{15}$ sec^{-1}, $\omega\tau$ is less than unity and the frequency effect small.

It is possible, however, that deep in the mantle σ_0 may be 100 times the above value. This leads to $\omega\tau \approx 1$, and in view of the uncertainties in the calculation, particularly as regards the value assigned to m^*, the existence of an important frequency effect cannot definitely be excluded.

The electrical conductivity in the outer mantle is about 10^{-4} ohm^{-1} cm^{-1}, and at a depth of about 600 km it rises to at least 10^{-2} ohm^{-1} cm^{-1} in a short interval of depth [*Lahiri* and *Price*, 1939]. The mean conductivity below 600 km is about 1 to 10 ohm^{-1} cm^{-1} [*Runcorn*, 1955]. Since $\alpha \approx 200\sigma$, the absorption coefficient deep in the mantle will be a few hundred cm^{-1} in the absence of a large frequency effect.

Pressure is likely to cause a shift in the position of the peak arising from exciton absorption rather than a large change in its intensity. Hence the effect of pressure on absorption is probably small compared with the effect of temperature.

Effect of temperature and pressure on the width of the pass band—The intensity of lattice absorption rises with temperature, and this narrows the pass band [*Schaefer* and *Matossi*, 1930; *Collins* and *Fan*, 1954]. But the importance of radiation at long wave lengths decreases as the temperature rises, and hence the effect of increasing intensity of lattice absorption is small.

The positions of the lattice absorption peaks shift towards shorter wave lengths as the pressure increases. In simple lattices the wave length of the fundamental absorption peak can be related to the compressibility χ and the density ρ by $\lambda_m \propto \bar{M}^{1/3}\chi^{1/2}\rho^{1/6}$ where $\bar{M}$ is a mean atomic mass [*Born* and *Huang*, 1954, footnote p. 111; an obvious misprint has been corrected]. The changes in χ and ρ in the mantle can be estimated from seismic data; for a given phase λ_m changes by about 40 pct between the surface and a depth of 600 km, and by about 50 pct between the surface and the base of the mantle. Since the temperature rises as the depth increases, this will not affect the opacity by more than a few per cent.

It is convenient to speak of the dependence of the position of the ultraviolet absorption edge on temperature and pressure in terms of the width of the energy gap E of the crystal. This is related to the frequency ν of the absorption edge by $E = h\nu$. Typical values of $(\partial E/\partial T)_P$ for solids range from -8×10^{-4} to -4×10^{-4} ev/°C [*Fan*, 1955; *Cronemeyer*, 1952]. The term $(\partial E/\partial P)_T$ may have either sign, and its magnitude typically ranges from 2×10^{-6} to 6×10^{-6} ev/bar [*Paul* and *Pearson*, 1954; *Fan*, 1955; *Long*, 1956]. *Runcorn* and *Tozer* [1955] give a value of -2×10^{-6} ev/bar for peridot. At depths less than 600 km, the shift in position of the ultraviolet absorption edge is too small to affect the opacity appreciably. An important indirect effect arises from the increase in electrical conductivity as the energy gap narrows.

Deep in the mantle, *Runcorn* [1955] finds that E may be as small as 1 ev. This corresponds to a

wave length of about 1.2 microns, implying that the pass band may be seriously narrowed at great depths.

The scattering coefficient—Most of the scattering in the mantle presumably takes place at grain boundaries. The problem may be further simplified by assuming that the scattering is by specular reflection at thin intergranular films. The scattering is evidently proportional to the average number of scattering centers per centimeter encountered by any pencil of radiation. The factor of proportionality is the reflection coefficient of a thin membrane, averaged over all angles of incidence; this quantity must be less than unity. The scattering coefficient is then less than d^{-1}, where d is the mean diameter of the crystals in the mantle. We have no direct information as to its probable magnitude, but observations on crustal rocks suggest that it should be of the order of centimeters rather than millimeters. The scattering coefficient is then of the order of 1 cm^{-1}, which is less than the uncertainty in the absorption coefficient.

Geophysical implications—The most primitive form of the theory of radiative transfer, in which the opacity is assumed independent of wave length, predicts that the radiative conductivity will be proportional to T^3. Calculations, using typical absorption spectra and (15), show that the cubic approximation is remarkably accurate up to temperatures of 2500°K. With this approximation, the radiative conductivity becomes

$$C_r = \frac{16n^2sT^3}{3\epsilon} \approx \frac{22 \times 10^{-12}T^3}{\epsilon} \text{ cal/cm sec°C}, \quad (16)$$

where s is the Stefan-Boltzmann constant; in the second equation n has been set equal to 1.7, a reasonable value for ferromagnesian silicates.

Present data suggest that ϵ is between 10 cm^{-1} and 30 cm^{-1} in rocks at room temperature. It increases with temperature largely because of an increase in electrical conductivity with temperature. Hence

$$\epsilon \approx \epsilon_0 + \frac{120\pi\sigma_0 e^{E/2kT}}{n} \quad (17)$$

where ϵ_0 is the opacity at low temperature. For olivine, E is about 3 ev and σ_0 about 10 ohm^{-1} cm^{-1} [*Runcorn* and *Tozer*, 1955]. $(\partial E/\partial T)_P$ is included in this value of σ_0; we shall neglect $(\partial E/\partial P)_T$. The radiative conductivity for several values of ϵ_0 and for the above values of E and σ_0 is shown in Table 3.

TABLE 3—*The radiative conductivity*[a] *as a function of temperature*

T	C_r cal/cm sec °C.		
	ϵ_0 = 5 cm^{-1}	ϵ_0 = 10 cm^{-1}	ϵ_0 = 30 cm^{-1}
°K			
500	0.001	0.000	0.000
1000	0.004	0.002	0.001
1500	0.015	0.007	0.002
2000	0.032	0.017	0.006
2500	0.048	0.028	0.011

[a] Values of the radiative conductivity were computed from the relation $C_r = \dfrac{22 \times 10^{-12}T^3}{\epsilon_0 + 2.2 \times 10^3 e^{-3/2kT}}$

Deep in the mantle the opacity is almost entirely determined by the electrical conductivity. The radiative conductivity then equals approximately $10^{-4}T^{*3}/\sigma$ where $T^* = 10^{-3}T$. If σ = 1 ohm^{-1} cm^{-1}, a temperature greater than 3000°K is required to make the radiative conductivity equal to the ordinary thermal conductivity at room temperature.

Although subject to large uncertainties, the data given in Table 3 suggest that in the outer part of the mantle the radiative conductivity may exceed the ordinary conductivity. At depths greater than about 600 km, the radiative conductivity decreases and may become inappreciable at a depth which can be specified only after the distribution of electrical conductivity in the Earth has been more accurately determined.

Changes in effective conductivity will be reflected in the thermal gradient in the mantle. Below the base of the crust the thermal gradient decreases, partly because the heat flow is smaller when the depth exceeds that of radioactive heat sources, and partly because of an increase in effective conductivity. At greater depths the effective conductivity decreases; an increase in thermal gradient may take place at these depths. This increase should accompany the rise in electrical conductivity at a depth of about 600 km, and the two phenomena may be intimately related.

Cooling of the Earth—A high effective conductivity in the outer part of the mantle implies that more of the Earth's initial heat has escaped during geologic time than has previously been supposed. In addition, the depth to which cooling has penetrated is greater with radiative transfer. The magnitude of the change brought about by radiative transfer can be estimated by considering the

effective conductivity of the outer 600 km of the Earth to be constant and twice that of the central portion. This rough model indicates that the amount of cooling in geologic time is approximately doubled by radiative transfer. This implies that about twice as much thermal contraction is available for mountain building, but it is not clear that even the increased amount of contraction is adequate.

The portion of the present heat flow at the surface that is of non-radiogenic origin is but little affected by the increased conductivity in the outer part of the mantle. *Jeffreys* [1952] found that roughly one-fourth of the heat flow was due to cooling of the Earth, and no drastic modification of this estimate is indicated. The depth to which the Earth has cooled appreciably is increased by two or three hundred kilometers by radiative transfer.

Concluding remarks—The contribution of radiation to the transfer of heat in the Earth has been considered in perhaps more detail than available data warrant. Measurements of the opacities of minerals are far too few to permit the drawing of definite conclusions, but it seems clear that radiative transfer takes place in the outer part of the mantle. The question is the importance of the effect rather than its existence.

Measurements of the opacity are required for a number of minerals. Studies of its dependence on temperature and pressure are best deferred until the more basic question of its dependence on composition and wave length is investigated. The spectral region of interest lies between the ultraviolet absorption edge and a wave length of roughly five microns.

The theory of radiative transfer presented here has never been subjected to stringent experimental test. It would be desirable to compare observed and computed conductivities at high temperatures.

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Abundance and Distribution of Uranium and Thorium in Zircon, Sphene, Apatite, Epidote, and Monazite in Granitic Rocks

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Abstract—Analyses were made of uranium and thorium in zircon, sphene, apatite, epidote, and monazite separated as accessory minerals from samples of granitic rock from widely scattered localities to indicate (1) the abundance, and (2) the natural distribution of these two components among the five mineral phases. The approximate distribution of the two elements in the accessory mineral phases, taken in pairs, is found to be as follows:

Minerals	Ratios	
	Uranium	Thorium
Zircon/sphene	7	2
Sphene/apatite	5	3
Apatite/zircon	0.1	0.3
Monazite/apatite	23	500
Sphene/epidote	10	2
Zircon/epidote	35	3
Apatite/epidote	3	0.7

No conclusions can be drawn on how close these ratios are to the true partition values, or the proximity to equilibrium conditions existing at the time of crystallization.

Introduction—The principal host minerals for uranium and thorium in the Earth's crust are zircon, sphene, apatite, epidote, and monazite, which occur as accessory minerals in crystalline rocks. This exploratory investigation was made to obtain an approximate measure of the amount and variation of these components in the accessory minerals, and also to see if there was any possibility of obtaining values for the partition of U and Th among these five mineral phases in natural samples by observation of the constancy of the distribution ratios.

Samples of the accessory minerals, generally about 99 pct pure, were obtained from a number of granitic rocks by standard specific gravity and magnetic methods [*Fairbairn*, 1955]. The rocks are dominantly granite except as noted in the tables, and concentrates were obtained from samples of about 50 lb. The uranium and thorium were measured by a method described by *Hurley* [1956] in which the 238 kev gamma ray from Pb^{212} in the thorium series is used to differentiate thorium against a total gamma-ray count in a two-channel scintillation spectrometer.

Errors—Hurley [1956] gives an estimate of the expectable errors in measurement. When the quantity of sample and activity is sufficient for a counting rate of at least twice background, the standard deviation error in measuring uranium or thorium is less than ten per cent if the constituent in question contributes an activity of at least 20 pct of the total. If the uranium activity is low compared to the thorium, or vice versa, the error in its measurement becomes large. The estimated errors are given in Figure 1. The uranium series has three times the activity of the thorium series, so that thorium values should be divided by three for a direct comparison of the relative activities of the two constituents. For example, if the thorium content is 12 pct of the uranium content, its contribution to the total gamma count is only about four

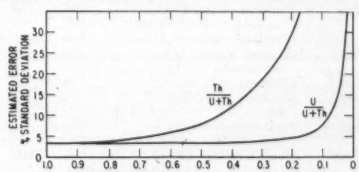

FIG. 1 – Estimated precision for different proportions of uranium and thorium, for single comparison against standard

TABLE 1–*Uranium and thorium content of accessory zircon from granitic rocks*[a]

Sample[b]	Locality	Quarry	Uranium[c]	Thorium[c]
			ppm	ppm
	Massachusetts			
3004 A	3 miles WSW of Peabody	Lineham	1210	375
B			510	205
C			405	130
3005 A	0.5 mile WNW of Rockport	Flat Ledge	2765	1890
B			2270	1200
C			1320	740
3006 A	2 miles WNW of Rockport	Blood Ledge	970	550
B			630	380
3011	2 miles W of Leominster	Leavitt	1130	380
3012 A	2 miles NE of Milford	Norcross	1350	480
B			955	445
3106 A	1.7 miles NNE of Milford	West	2400	915
B			2080	705
C			1425	490
3014 B	2.5 miles ESE of Wrentham		1325	680
3013 A	1.5 miles WNW of	Blanchard	2040	1090
B	Uxbridge		1875	750
C			650	480
3052	8.2 miles N of North Attleboro		1820	900
3051	3 miles N of North Attleboro		1500	390
3107 A	North end of Whitinsville		1640	1000
3050 A	SW side of Hoppin Hill,		2000	2100
B	North Attleboro		1540	1400
1982	Dedham, on Route 1		670	380
	Nova Scotia			
2090 A	Route 3 outside of Halifax		770	75
2093 A[d]	Route 3, Birchtown, Shel-	Dauphine	1900	500
B	burne County		1550	450
2094	1 mile E of Atwood's Brook, Shelburne County, Route 3		680	60
2096 A	0.5 mile E of Albany Cross		830	160
B	on Route 10, Annapolis County		620	75
2097	1 mile S of Springfield, Route 10		840	<100
2098	3.5 miles N of New Ross, Route 12		850	100
2099 A	8 miles S of Kentville,		630	100
B	Route 12, Kings County		560	180
	Miscellaneous			
3086 A	Murray granite, Sudbury,		1700	460
B	Ontario		1200	280
3078	7 miles S of Calais on Route 1, Maine		2540	1100
3063	Hollingsworth and Whitney Road, 6 miles W of Route 201, Maine		1030	460
3087	Creighton granite, Sudbury, Ontario		3000	490
3125	Lausitz-massif, Germany		950	525
1819	Max Patch, North Carolina		237	90
1644	Beach sand concentrate, North Carolina		312	74
	Climax, Colorado[e]		2450	1120

[a] All rocks are granites unless otherwise noted.

[b] Samples were separated into different fractions according to magnetic susceptibility, and these were designated A, B, and C in order of decreasing susceptibility.

[c] Errors in these analyses are discussed in the text.

[d] Quartz diorite.

[e] Silica-rich metasomatic rock.

per cent, and the estimated error in measurement of the thorium as obtained from Figure 1 is then 17 pct. On the other hand the error for the major constituent, uranium, is only four per cent.

Results—The results of the analyses showing the abundances of U and Th in the different minerals are given in Tables 1 to 7. Table 8 shows the average ratios of thorium to uranium in the different minerals. In Table 9 examples are listed in which two minerals from the same rock have been analyzed, so that the distribution of uranium and thorium in the two phases can be observed.

In Figure 2 the distribution of uranium and thorium in the accessory mineral phases is shown for three of these phases at a time. Only four examples are shown, but other combinations can be drawn from the average figures given in Table 9. It was not possible to obtain three accessory phases from the same sample of granite so that the rough distribution of uranium or thorium in the different phases had to be obtained from samples yielding two of the phases at a time. Thus in Figure 2a, for example, the distribution of uranium and thorium in zircon and sphene was obtained from the average of several granite samples as listed in Table 9A. Similarly the distribution of uranium

TABLE 2 – *Uranium and thorium content of coarse crystals of zircon from pegmatites*

Sample	Locality[a]	Uranium	Thorium
		ppm	*ppm*
1661	Iredell County, North Carolina	580	500
1669	Buncombe County, North Carolina	730	1650
1659	Renfrew County, Ontario	140	10
1660	Brudenell Township, Ontario	105	50
1795	Haliburton County, Ontario	3520	1080
1800	N. Hastings County, Ontario	3550	3020
1799	N. Hastings County, Ontario	4380	3840
1801	Madawaska, Ontario	25,200	1600
1805	Haliburton County, Ontario	5380	500
1797	Grattan Township, Ontario	6400	1050
1681	Leeds County, Ontario	81	93
1962	Wilberforce, Ontario (acid treated)	4000	(100)
1958	Oklahoma (nonmetamict)	300	675
1960	Oklahoma (metamict)	1550	7500
1678	Hammond, New York	1570	600
1677	Lewis County, New York	800	10
1915	Tigerville, North Carolina	575	1020
1664	El Paso County, Colorado	480	2070
2088	South Africa	1020	355
1825	Litchfield, Maine	535	340
3038	Ceylon	5850	600

[a] These samples were obtained mostly from museum collections with little information available on exact location.

TABLE 3 – *Uranium and thorium content of accessory sphene from granitic rocks*[a]

Sample	Locality	Uranium	Thorium
		ppm	*ppm*
3060	Mount Waldo, Maine	1270	165
3058	Sprucehead Island, Maine	105	20
3055	Hallowell, Maine	190	140
3062	5.5 miles S of Jackman, Maine, Route 201	120	430
3063	Hollingsworth and Whitney Road, 6 miles W of Route 201, Maine	250	375
3071	St. Gideon, Quebec	214	<40
3079	1 mile S of Jonesboro, Route 1, Maine	39	80
3081	Barriefield, Ontario, near Kingston	165	600
3080	2 miles N of Mt. Desert, Route 198, Maine	245	950
3082[b]	6 miles N of Kingston, Ontario	70	150
3084	Gaspe, 7 miles S of Gaspesie, Quebec	55	150
3085	West end of Mountainville, Maine	300	1070
3051	3 miles N of North Attleboro, Massachusetts, Route 1	160	90
3014	2.5 miles ESE of Wrentham, Massachusetts	155	325
3008	McCarthy quarry, Massachusetts	175	3150
2093[c]	Birchtown, Shelburne County, Nova Scotia, Route 3	280	180
3069[d]	St. Josef's Blvd., Montreal	25	90
1968[e]	Idaho	370	900
1969[e]	Idaho	206	190
1970[f]	Clayton Cone, Utah	400	560
	Alta Stock,[f] Utah	287	350
1971[g]	Blueberry Mountain, Massachusetts	1380	2430
1684[h]	Franklin, New Jersey	215	190
1677[h]	Lewis County, New York	218	170
1782[i]	Nipissing district, Ontario	127	70

[a] All samples are granites unless otherwise noted.
[b] Syenite.
[c] Quartz diorite.
[d] Tinguaite.
[e] Gneiss.
[f] No information.
[g] Metasomatic contact rock.
[h] Metamorphic rock.
[i] Pegmatite.

and thorium in zircon and apatite (Table 9C), and in apatite and sphene (Table 9B), was obtained independently from different sets of granite samples from rocks of differing ages in widely scattered localities.

In Figure 2 the locations of uranium and thorium on the diagram, indicating their distribution in the accessory minerals, were obtained by the intersection of three lines drawn from each apex and dividing each base in the proportion found for the pair of minerals at either end of the base. The intersections of these lines form the triangles shown on the figure. The size of each triangle indicates how closely the lines came to intersection at a point, and thus is an indication of the analytical error or the constancy of the distribution of uranium and thorium in these three minerals. The values are averages only. Individual ratios may

TABLE 4 – *Uranium and thorium content of accessory apatite from granitic rocks.*[a]

Sample	Locality	Uranium	Thorium
		ppm	*ppm*
2090	Route 3 outside of Halifax, Nova Scotia	95	80
2092	3.8 miles E of Port Monton, Nova Scotia	80	<15
2093[b]	Birchtown, Shelburne County, Nova Scotia	30	30
2095	W. Nictaux, Annapolis County, Nova Scotia	215	<40
2096	0.5 mile E of Albany Cross, Route 10, Nova Scotia	90	80
2097	1 mile S of Springfield, Route 10, Nova Scotia	140	95
2098	3.5 miles N of New Ross, Route 12, Nova Scotia	105	80
2099	8 miles S of Kentville, Kings County, Nova Scotia	85	50
2100	Near Shelburne, Nova Scotia	85	400
3007	Harris quarry, Massachusetts	10	10
3008	McCarthy quarry, Massachusetts	150	5
3011	2 miles W of Leominster, Massachusetts	20	10
3042	Westerly, Rhode Island	10	20
3059	Lincolnville quarry, Maine	85	100
3055	Hallowell, Maine	55	80
3085	Mountainville, Maine	40	100
3056	N. Jay, Maine	50	50
3057	Waldoboro, Maine	50	10
3063	Hollingsworth and Whitney Road, Maine	60	120
3066	Scotstown, Quebec	160	5
3067	Brome Mountain, Quebec	25	85
3065	Mount Megantic, Quebec	50	75
3068[c]	Mount Johnston, Quebec	10	40
3070	Chicoutimi, Quebec, Route 54 S of Route 16A	30	60
3074	N side of Bagotville, Quebec	75	50
3078	7 miles S of Calais, Route 1, Maine	100	250
3073	Kenogami, Route 54, Quebec	<10	<10
3081	Barriefield, Ontario, near Kingston	10	20
3082[d]	6 miles N of Kingston, Ontario	5	5

[a] All samples are granites unless otherwise noted.
[b] Quartz diorite.
[c] Essexite.
[d] Syenite.

TABLE 5 – *Uranium and thorium content of coarsely crystalline apatite*

Sample	Locality	Uranium	Thorium
		ppm	ppm
1654	Durango, Mexico	10	250
1658	Wilberforce, Ontario	285	1600
1656	Bedford Township, Ontario	30	160
1657	Snarum, Norway	40	40
1655	Templeton, Quebec	20	260

TABLE 6 – *Uranium and thorium content of monazite concentrates from granites (percentage concentration mostly 80 pct.)*

Sample	Locality	Uranium	Thorium
		ppm	ppm
2092	3.8 miles E of Port Mouton, Nova Scotia	3,000	39,000
2096	0.5 miles E of Albany Cross, Route 10, Nova Scotia	Low[a]	26,000
2100	Near Shelburne, Nova Scotia	Low	75,000
3008	McCarthy quarry, Massachusetts	2,000	50,000
3042	Westerly, Rhode Island	Low	75,000
3078	7 miles S of Calais, Route 1, Maine	1,200	33,500
3055	Hallowell, Maine	Low	44,000
3056	North Jay, Maine	2,500	51,000
3066	Scotstown, Quebec	2,500	50,000
3109	6 miles W of Lowell, Massachusetts	Low	58,000
3107	Whitinsville, Massachusetts	50,000[b]	45,000

[a] Low means probably less than five per cent of thorium values (see discussion under Errors).

[b] Probably a uranium-bearing mineral in concentrate.

TABLE 7 – *Uranium and thorium content of accessory epidote from granites*

Sample	Locality	Uranium	Thorium
		ppm	ppm
3063	Hollingsworth and Whitney Rd., Maine	27	160
3008	McCarthy quarry, Massachusetts	27	86
3062	Jackman, Maine	30	73
3051	3 miles N of N. Attleboro, Massachusetts	40	26
1982	Dedham, Massachusetts	43	185
3085	Mountainville, Maine	23	65
3058	Sprucehead Island, Maine	2	400
3014	Wrentham, Massachusetts	23	260
3079	Jonesboro, Maine	175	600

TABLE 8 – *Average ratios of thorium to uranium in the different minerals*

Mineral	Ratio Th/U
Accessory zircon	0.4
Pegmatite zircon	1.0
Accessory apatite	1.3
Pegmatite apatite	10
Accessory sphene	1.7
Monazite	~25
Epidote	4.8

depart considerably from the average values, but it is difficult to tell at this stage of development of the analytical techniques how much is true variability and how much is due to precision errors in analysis. In monazite the values for the distribution have an uncertainty that results from a low proportion of inert impurities in the monazite concentrates and from the difficulty of measuring the uranium in the presence of such high proportions of thorium.

The data are presented with no conclusions because the authors feel that although the measurements are worth reporting as an indication of the natural abundance and distribution of these elements in these accessory phases, the distribution ratios have shown enough variability so that it is not possible to say how close these observed and calculated average ratios might be to the true partition values.

Furthermore, it seems probable that equilibrium conditions did not exist during the crystallization of the pairs of phases as measured. Because the tolerance of the crystal structures of these five minerals for uranium and thorium (regardless of the mode of substitution) is undoubtedly a function of temperature and pressure, it would not be expected that the distributions would be identical in each sample of granite. If the distribution factor giving the ratio of uranium in the solid phase to that in the fluid phase at time of crystallization is less than 1, the high concentration of uranium in the final interstitial fluid may upset the ratios because of the development of a late phase which may be intimately associated with the earlier rock-forming minerals. Evidence for this association is observed in autoradiographs of polished surfaces of granite which show concentration of uranium along grain boundaries, and also in acid leaching experiments [*Hurley*, 1950; *Larsen* and others, 1956] which demonstrate that this interstitial material containing the radioactive elements is

TABLE 9 – *Distribution of uranium and thorium between pairs of accessory minerals from granitic rock samples. Values in parts per million*

Sample	Uranium		Thorium	
A	Zircon	Sphene	Zircon	Sphene
3014	1325	155	680	325
3051	1500	160	390	90
2093	1700	280	475	180
3063	1030	250	460	375
Average	1390	210	500	240
Ratio, zircon to sphene	6.6		2.1	
B	Sphene	Apatite	Sphene	Apatite
3058	105	40	20	60
3055	190	55	140	80
3063	250	60	375	120
3082	70	5	150	5
2093	280	30	180	30
Average	180	40	175	60
Ratio, sphene to apatite	4.7		2.9	
C	Apatite	Zircon	Apatite	Zircon
3011	20	1130	10	380
2090	95	770	80	75
2093	30	1700	30	475
2096	90	720	80	120
2097	140	840	95	<100
2098	105	850	80	100
2099	85	630	48	100
3063	60	1030	120	460
Average	80	960	70	215
Ratio, apatite to zircon	0.08		0.32	
D	Monazite	Apatite	Monazite	Apatite
2092	3000	80	39,000	<15
2096		90	26,000	80
2100		85	75,000	400
3008	2000	150	50,000	5
3042[a]		10	75,000	20
3078[a]	1200	100	34,000	250
3055[a]		55	44,000	80
3056[a]	2500	50	51,000	50
3066	2500	160	50,000	5
Average	2000	85	50,000	95
Ratio, monazite to apatite	>23[a]		>530[a]	
E	Zircon	Epidote	Zircon	Epidote
3063	1030	27	460	160
3051	1500	40	390	26
1982	670	43	380	185
3014	1325	23	680	260
Average	1131	33	477	158
Ratio, zircon to epidote	34.3		3.0	

TABLE 9 – *Continued*

Sample	Uranium		Thorium	
F	Apatite	Epidote	Apatite	Epidote
3063	60	27	120	160
3008	150	27	5	86
3085	40	23	100	65
Average	83	26	75	104
Ratio, apatite to epidote	3.2		0.72	
G	Sphene	Epidote	Sphene	Epidote
3063	250	27	375	160
3062	120	30	430	73
3051	160	40	90	26
3085	300	23	1070	65
3058	105	2	20	400
3014	155	23	325	260
Average	182	18	380	164
Ratio, sphene to epidote	10		2.3	

[a] Pure monazite values would exceed those for concentrate by several per cent.

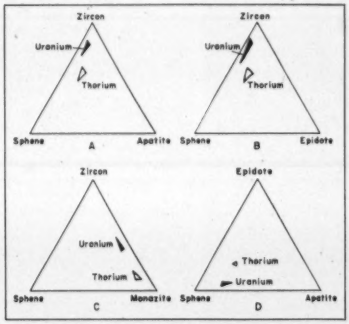

FIG. 2 – Distribution of uranium and thorium among three accessory mineral phases for four combinations of accessory minerals; data from Table 9

soluble in dilute acids whereas most of the accessory minerals are not soluble.

Most granites have a ratio thorium/uranium of about three for the whole rock. Because zircon, sphene, and apatite have a smaller ratio than this, it seems likely that much of the interstitial radioactive material has a Th/U ratio higher than three.

Despite all the variability, the erratic cases, and the probability of non-equilibrium crystallization the average ratios were found to be mutually consistent as seen in Figure 2, which suggests (but

does not prove) that they may possibly be fairly close to some average partition values for the range of temperature through which the accessory mineral crystallization took place in these granitic rocks.

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Determination of Radiogenic Helium In Zircon by Stable Isotope Dilution Technique*

PAUL E. DAMON AND J. LAURENCE KULP

Abstract—Standard zircon samples studied earlier by Hurley, Larsen, and Gottfried (1955) have been analyzed for helium by an isotopic dilution technique using He^3 as a spike yielding an accuracy of about ±3 pct. The quantity of helium obtained is about 15 pct higher than that obtained by earlier volumetric techniques. Alpha activity determinations agree closely with earlier work. Measurements on non-metamict zircons from Ontario, Ceylon, and Oklahoma suggest that helium retentivity in excess of 80 pct is not unusual. Metamict zircons on the other hand may have retained only one per cent of radiogenic helium. Total irradiation is not the only factor in determining the quantity of helium retained. A helium age method is still possible under proper conditions.

Introduction—The helium method of geochronometry has not been able to produce consistently correct ages [*Keevil*, 1941; *Hurley*, 1954]. In addition to inherent difficulties such as incomplete retention of radiogenic helium by rocks and minerals, there have been serious experimental errors incurred by lack of proper standards and other technical limitations [*Evans* and others, 1939]. Retentivity studies were also hampered by the lack of reliable geochronological data for the sample measured. Nevertheless, it was quite obvious that most minerals and rocks did not give reasonable ages by the helium method, although a few minerals such as zircon and magnetite showed some promise.

A study of the helium retention of zircon and sphene by *Hurley* [1952] seemed to indicate that helium leakage was proportional to the total alpha irradiation. A later comparison of radiogenic helium and lead in non-metamict zircons [*Hurley, Larsen,* and *Gottfried*, 1956] suggested a rather uniform discrepancy such that the amount of helium was only 75 pct of the amount expected from the lead content. These results were not consistent with the earlier work and as it was difficult to comprehend a process that would result in a uniform loss of helium despite difference in age and irradiation, the question was left open.

It is the purpose of this paper to report a reexamination of the retention of helium in zircon.

The small zircon samples remaining from their investigation were made available for the present study through the kind cooperation of Hurley and Gottfried. The helium content was redetermined by the isotope dilution technique described below.

* Lamont Geological Observatory Contribution No. 261.

Experimental Techniques

Gas liberation and purification—The vacuum fusion technique described by *Carr* and *Kulp* [1957] was used for gas liberation and purification. He^3 containing only about one part per thousand He^4 was used as the tracer. (Obtained on A.E.C. allocation from the Radioisotope Sales Department, Operations Division, ORNL.) A schematic diagram of the vacuum fusion system is shown in Figure 1.

The zircon samples were fused by induction heating in a nickel crucible with 1:1 borax-sodium carbonate flux. The flux was formed into a cake by melting in a nickel crucible. The sample was weighed in another crucible and the cake, which had been kept in a desiccator was placed on top of the sample.

It was necessary, because of evaporation, to increase the temperature slowly in order to keep the flux molten but without violent boiling. A crucible lid was used to prevent the loss of incompletely fused sample by splattering. In three cases fresh flux was added at the end of a zircon run, and the mass was fused again. In all instances no significant additional helium was observed. The He^3 tracer was introduced after the flux became molten.

Helium was pumped out of the furnace system into the purification and collection system by a small mercury diffusion pump. Proper operation of the diffusion pump was insured by keeping the charcoal trap at liquid nitrogen temperature. Experience has shown that the zircon sample was completely dissolved and the helium released soon after the flux became molten. In practice the sample was maintained as a melt for about an hour after which the temperature was lowered. Pumping was con-

tinued for another 30–60 minutes to insure complete evacuation of the furnace. At the end of this time the stopcock to the furnace was closed, the liquid nitrogen was removed from the charcoal trap and the chemically active gases were reacted with hot calcium. Five to ten minutes of purification at 700°C temperature was quite adequate. After purification the liquid nitrogen was replaced on the charcoal to remove most of the hydrogen remaining after the calcium purification. The helium was then forced into the break seal ampoule by means of a Toepler pump and the ampoule was sealed off and removed to the mass spectrometer.

Five blank fusion runs yielded between 6×10^{-8} standard cc to 6×10^{-5} standard cc of helium per run. The lower value is about that which is expected from diffusion through the glassware during an average fusion, whereas the upper value probably represented a small leak. The presence of neon in the purified gas served as a leak detector. The amount of helium corresponding to a given signal height of neon was determined for this work by introducing a known amount of air into the furnace during a blank fusion run. In practice the helium blank was always less than one per cent of the helium from the zircon samples.

Mass spectrometry—The mass spectrometer is a first order, direction focusing, 60°, 6-inch radius of curvature instrument described by *Carr* and *Kulp* [1957]. A one-mil molecular leak, an exit slit of eight-mil width and a collector slit of 30-mil width were used. The overall sensitivity was such that 10^{-8} standard cc of helium or neon introduced into the fusion system could be detected.

The isotope dilution technique, in which the He^3 tracer was compared with known amounts of He^4, eliminated the problem of isotopic fractionation caused by the flow of the gas into the mass spectrometer. The ratio at zero time before fractionation of the gas in the reservoir was determined graphically for both known and unknown by plotting the observed ratio against time. Thus essentially a known quantity of He^4 is compared with an unknown quantity of He^4 at zero time by reference to the calibrated He^3 tracer.

It was necessary to adjust the source magnets for maximum peak height before each helium determination. If this were not done the He^4/He^3 ratio was dependent upon the focus potential. This dependence is greatest at maximum trap current or when the source magnets are completely removed. At maximum peak height the trap current was reduced by a factor of three but both He^4 and He^3 were in focus at the same focus voltage setting. If the trap voltage is decreased, the trap current increases, the peak heights decrease and a dependence of the He^4/He^3 ratio on the focus plate voltage is observed. The probable explanation of this effect is that maximum trap current does not correspond to direct entry of the electron beam into the trap collector but rather the trap current is greatly increased by secondary emission when the beam is misfocused onto the block. This results in ions being created at varying distances from the exit slit rather than within a well-defined electron beam.

During the mass spectrometric determination of helium the neon peak at $m/e = 20$ and the H_2^+ peak at $m/e = 2$ are also scanned. Contributions at mass 20 from H_2O^{18} and doubly ionized A^{40} were eliminated by the purification process and retention

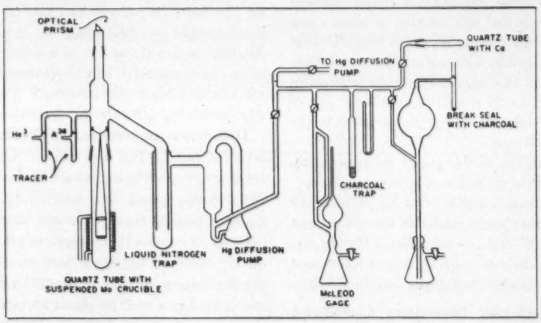

FIG. 1 — Inert gas liberation and purification system

on charcoal at liquid nitrogen temperatures. The H_2^+ peak was scanned to insure that no error was introduced due to the contribution of H_3^+ to the $m/e = 3$ peak. In practice, this was not a significant source of error.

Isotope dilution technique—The *Balestrini* [1954] type of 'spike' preparation system described by *Carr* and *Kulp* [1957] was replaced by a system similar to that described by *Ingrahm* [1954]. The seal-off of the break seals by the Balestrini method was extremely critical. A slight difference in the time of sealing off of the tracer ampoules could result in a significant pressure differential. On the other hand by a proper choice of capillary to manifold dimensions the Ingrahm system can be made self-compensating for small differences in the time of sealing off of the tracer ampoules. The first ampoule to seal off and the last ampoule to seal off are used in tracer calibration. Experience has shown that the difference in pressure is less than two per cent.

The standard preparation system is shown in Figure 2. It provides a simple method for obtaining small exact quantities of He^4 as follows: (1) The system is evacuated and a static leak test is run for a half hour. (2) If the leak test is successful ($P < 1.5 \times 10^{-5}$ standard cc in $\frac{1}{2}$ hour), the system is re-evacuated and the system isolated from the pumps. The five-liter reservoir is shut off from the system (stopcock 3 closed). (3) Helium is introduced into the system from the storage bulbs, allowed to equilibrate, and the pressure is read on the manometer. (4) Stopcock 2 is closed and the manifold is pumped out. (5) Stopcock 1 to the storage system is closed, stopcock 2 is opened, and the gas is allowed to equilibrate with the reservoir which is now also opened (stopcock 3) to the break seal ampoule. (6) After equilibration (one hour is sufficient) the stopcock to the tracer ampoule is closed and the tracer ampoule sealed off with a fine tipped flame to prevent excessive heating. The presence of the dummy insures that, except for the slight decrease in volume caused by sealing off, no gas is transferred preferentially to or from the tracer ampoule. The volume of the break seal ampoule includes the volume of the capillary up to the seal off point.

The derivation of the standardization formula is as follows:

Let P_i = initial pressure
T_i = temperature at the time the pressure is read from the manometer
V_1' = the total volume on the break seal ampoule side of the stopcock 2. This is equal to V_1 (volume of the break seal ampoule) + V_d (volume

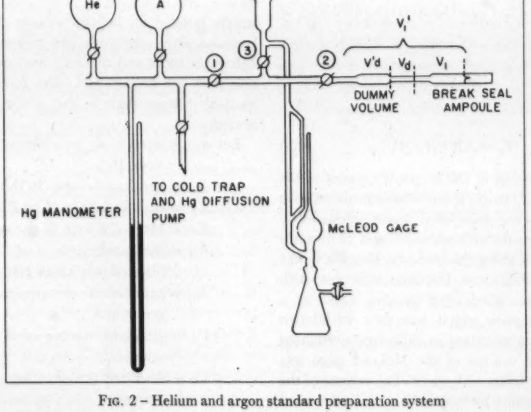

FIG. 2 – Helium and argon standard preparation system

of the joining capillary) + V_d' (volume of the dummy ampoule)

P_{eq} = pressure after equilibration with the reservoir

V_2 = volume on the reservoir side of stopcock 3+ connecting glassware between stopcocks 1, 2 and 3

P_s, V_s, T_s = pressure, volume and temperature under standard conditions

Now equating PV/T before and after expansion (T_i is constant)

$$\frac{P_i V_1'}{T_i} = P_{eq}\frac{(V_1' + V_2)}{T_i} \tag{1}$$

Solving for P_{eq}

$$P_{eq} = \frac{P_i V_1'}{(V_1' + V_2)} \tag{2}$$

also

$$\frac{P_{eq} V_1}{T_i} = \frac{P_s V_s}{T_s} \tag{3}$$

and solving again for P_{eq}

$$P_{eq} = \frac{P_s V_s T_i}{V_1 T_s} \tag{4}$$

Eq. (2) and (4) may be equated and solved for V_s

$$V_s = \frac{T_s V_1 V_1' P_i}{T_i P_s (V_1' + V_2)} \tag{5}$$

substituting for the constant terms (since V_1' is small compared to V_2 and an average value may be assumed)

$$K = \frac{T_s}{P_s(V_1' + V_2)} \tag{6}$$

we have

$$V_s = K P_i V_1 V_1'/T_i \tag{7}$$

Since the volume of the ampoule appears in the numerator of (7) twice, it must be determined with precision. This was done for all tracer ampoules by filling the ampoule with mercury, and then withdrawing and weighing the mercury. Because it was impractical to fill the five-liter reservoir with mercury, it was filled with distilled water at a known temperature which was then withdrawn and the volume measured in calibrated graduated cylinders. The volume of the McLeod gage was determined by filling with water. The volume of the manifolds bounded by stopcocks 1, 2, and 3 need only be estimated from the physical dimensions of the connecting glassware because it contributes little to the denominator of (6). (However, it also was determined precisely by filling with mercury.) The error incurred by making these approximations is less than 0.1 pct.

The pressure readings P_i for successive standard ampoule preparations should lie on a smooth curve. A discontinuity in the curve would be an indication of a leak. During one standard preparation, the stopcock 2 was left open. Comparison with standards prepared properly showed that ten per cent of the gas computed to be in the ampoule at equilibration had been lost to the reservoir.

Standards prepared in this way have been checked by standards measured by a precise McLeod gage and by intercalibration with other laboratories [*Carr* and *Kulp*, 1957] with good agreement. The method is simple and sufficiently accurate.

For each He^3 tracer preparation at least two ampoules of the tracer are compared with two different standards. In order to check equilibration of the tracer and sample in the vacuum fusion system standards and tracers were introduced into the furnace and carried through a mock fusion at high temperatures. However, comparison with tracers and standards equilibrated in the mass spectrometer manifold or in the vacuum fusion system did not indicate that there was any systematic difference.

In the stable isotope dilution analysis the technique is simplified if the tracer, standard and unknown are monisotopic. This condition is very nearly fulfilled for helium because the He^3 tracer contains only one part per thousand He^4 and helium in rocks and minerals contains only about one part per million He^3. The following mathematical relationship is for a two component system:

Let A = isotope to be determined (in this work He^4)

B = enriched isotope (in this work He^3)

R_T = ratio of isotope A to B in the tracer

R_X = ratio of B to A in the sample

R_M = measured ratio of A to B in equilibrated mixture of tracer and sample

R_C = ratio of A in sample to B in the tracer = V_A/V_B

V_A = standard volume of A contained in sample

V_B = standard volume of B in tracer ampoule

V = physical volume of the tracer ampoule

then

$$R_M = \frac{(V_A + V_B R_T)}{(V_A R_X + V_B)} \tag{8}$$

Dividing both numerator and denominator by V_B and substituting R_C for V_A/V_B

$$R_M = \frac{(R_C + R_T)}{(R_C R_X + 1)} \tag{9}$$

solving for R_C

$$R_C = \frac{(R_M - R_T)}{(1 - R_M R_X)} = \frac{V_A}{V_B} \tag{10}$$

define a constant L (volume of tracer per unit of ampoule)

$$L = V_B/V \tag{11}$$

but to calibrate the tracer a known amount of the isotope to be determined is compared with the tracer, and L is calculated from (11).

Substituting for V_B from (10)

$$L = V_A/R_e V \tag{12}$$

L is calculated from several such tracer calibrations, the average value of L is then used for calculation of V_A in the samples.

$$V_A = L R_e V \tag{13}$$

It should be clear that the standard volumes involved are partial volumes for a single isotope and not the total gas volume in the ampoules. The total gas volume of the standard used in calibration must therefore be corrected for composition.

Alpha counting—An alpha scintillation counter of the type described by *Kulp, Holland,* and *Volchok* [1952] was used. The counter utilized a Dumont type 6292 flat faced, two-inch diameter photomultiplier with Dupont 1101 phosphor.

The reproducibility for counting zircons was only slightly less than that determined from random count statistics. The zircons were counted relative to a standard zircon from Oklahoma. The uranium and thorium content of this zircon had been precisely determined by isotope dilution. (The standard zircon was provided by George Tilton of the Carnegie Institution Geophysical Laboratory; 414 ± 4 ppm uranium; 1337 ± 13 ppm thorium).

Summary of analytical precision—Mock fusion experiments introducing known amounts of He^3 and He^4 (eight in number) and replicate measurements on minerals (nine in number) gave a standard deviation of three to five per cent. The precision approached the lower limit in later work because of improved mass spectrometric technique. Initially the mass spectrometric technique was the dominant source of error. For later work the mass spectrometry contributed a small part of the observed differences, which were probably due to lack of complete equilibration of spike and sample helium and sample inhomogeneity.

The reproducibility of the zircon data determined from replicate measurements was two per cent standard deviation.

As mentioned previously, care was taken to avoid possible systematic errors. For example, mock fusion experiments were made in which known quantities of He^3 and He^4 were introduced into the furnace at high temperatures, carried through typical purification processes of different duration, collected in an ampoule and compared mass spectrometrically. Several different He^3 tracer preparations were used during the course of this work.

Decay Constants and Equations for the Alpha-Helium Method

The uranium and thorium decay scheme and decay constants are well known and have recently been summarized by *Kulp, Bate* and *Broecker* [1954]. U^{238} decays through various daughter products to Pb^{206} yielding eight helium atoms per Pb^{206} atom. Similarly U^{235} decays to Pb^{207} yielding seven helium atoms per Pb^{207} atom and Th^{232} decays to Pb^{208} yielding six helium atoms per Pb^{208} atom. Sm^{147} and Bi^{209} are also alpha emitters but their long half lives make the helium production too small for useful measurement.

The quantity of helium produced in time t is

$$N_{He} = K_i(N_i^0 - N_i) \tag{14}$$

where N_{He} = no. of helium atoms produced from time t to present

N_i^0 = no. of initial parent atoms at time t (U^{238}, U^{235} or Th^{232})

N_i = no. of initial parent atoms at present time (U^{238}, U^{235} or Th^{232})

K_i = no. of helium atoms produced per lead atom in each decay series

But according to the elementary exponential decay law

$$N_i^0 = N_i e^{\lambda_i t} \tag{15}$$

where λ_i = the decay constant for the particular parent isotope and so substituting in (14)

$$N_{He} = \sum_i K_i N_i (e^{\lambda_i t} - 1) \tag{16}$$

Since Avogadro's number is equivalent to 22.4×10^6 microliters volume, the amount of helium in microliters is

$$\text{He} = \frac{N_{He} \times 22.41 \times 10^6}{6.023 \times 10^{23}} = \frac{22.41 \times 10^6}{6.023 \times 10^{23}} \sum_i K_i N_i (e^{\lambda_i t} - 1) \tag{17}$$

For the alpha helium method it is necessary to express N_i in units of alpha per mg hr (a) corresponding to the measured alpha activity

$$a = a_{238} + a_{235} + a_{232} \tag{18}$$

and

$$a_{238} = 8N_{238}\lambda_{238}, \qquad a_{235} = 7N_{235}\lambda_{235}$$

and $$a_{232} = 6N_{232}\lambda_{232}$$

If the N's are expressed in units of atoms per gram

$$\text{He} = 3.26 \times 10^{-10} \sum_i \frac{a_i}{\lambda_i} (e^{\lambda_i t} - 1) \text{ microliters per gram} \tag{19}$$

For a mineral containing only thorium all of the activity is from the thorium series and $\lambda_{232} = 0.4987 \times 10^{-10}$ yr^{-1}.

In this case

$$\text{He} = 6.541a\,(e^{0.4987 \times 10^{-10} t} - 1) \text{ microliters per gram} \tag{20}$$

For a mineral containing only uranium and no thorium the U^{235}/U^{238} total alpha activity ratio is

$$A = \frac{a_{235}}{a_{238}} = \frac{K_{235}\lambda_{235}N_{235}}{K_{238}\lambda_{238}N_{238}} \tag{21}$$

but

$$N_{235} = \frac{1}{137.7} N_{238} \tag{22}$$

and so, substituting (22) into (21)

$$A = \frac{K_{235}\lambda_{235}}{K_{238}\lambda_{238}} \frac{1}{137.7} = 0.0401 \tag{23}$$

where

$K_{235} = 7$, $K_{238} = 8$,

$\lambda_{235} = 0.9722 \times 10^{-9}$ yr^{-1},

$\lambda_{238} = 0.1541 \times 10^{-9}$ yr^{-1}.

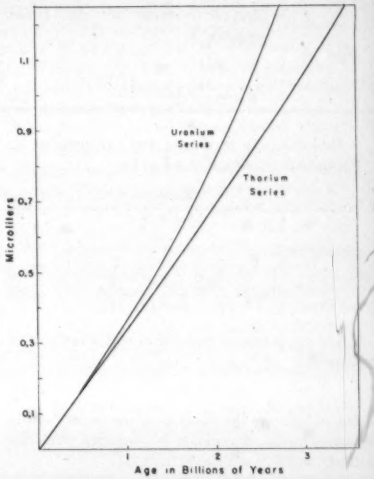

FIG. 3 – Helium production versus Time (for one gram of mineral with one alpha per mg per hour activity)

Thus the proportion of the alpha activity due to the U^{235} series will be $0.0386 = A/(1 + A)$ and from U^{238} series $0.9614 = 1/(1 + A)$.

For the uranium series then

$$\text{He} = 3.262 \times 10^{-10} \frac{a}{(1 + A)} \left[\frac{1}{\lambda_{238}} (e^{\lambda_{238} t} - 1) + \frac{A}{\lambda_{235}} (e^{\lambda_{235} t} - 1) \right] \tag{24}$$

and substituting the numerical values of the decay constants

$$\text{He} = 2.035a(e^{0.1541 \times 10^{-9} t} - 1) + 0.01295a(e^{0.9722 \times 10^{-9} t} - 1) \tag{25}$$

The helium production calculated from these equations for pure thorium and pure uranium series emitters is shown graphically in Figure 3. Unless additional information is available concerning the U/Th ratio for the mineral, the accuracy of the alpha-helium method is limited by the different helium production rates as may be seen from Figure 3. At about 300 million years the uncertainty in age resulting from a lack of this information is ±1 per cent and at about one billion years the uncertainty is ±3.5 per cent, while at the age

of the oldest rocks which have been dated (2.7 billion years) the uncertainty is approximately ±11 pct.

Results

The results of the isotope dilution determination are compared in Table 1 with the earlier work by the volumetric method. The helium contents determined by isotope dilution are on the average 15 pct higher than for the older work.

The alpha activity of several of the zircon samples provided by Hurley and Gottfried were also redetermined (Table 2). The results are in close agreement with the alpha counting data of *Hurley, Larsen,* and *Gottfried* [1955]. However, earlier results by alpha counting [*Hurley*, 1952] for identical samples were on the average ten per cent lower.

TABLE 1 – *Alpha-helium method intercalibration: helium content*

Sample[a]	*Hurley* [1952]	*Hurley, Larsen,* and *Gottfried* [1955]	This work	Ratio of volumetric to isotope dilution determinations
	μl/gm[b]	μl/gm	μl/gm	
Ontario				
1659....	7.40	7.80	9.26 ± 0.33	0.80
1670a...	16.18	16.18	21.0 ± 0.8	0.70
1660....	7.42	7.42	9.93 ± 0.35	0.75
1681a...	7.15	7.15	7.39 ± 0.26	0.97
Average...				0.82
Ceylon				
3002....	...	64.9	75.8 ± 3.8	0.86
3027....	...	170.0	196 ± 7	0.87
Average...				0.86

[a] Location of Ontario samples: 1659, Renfrew County; 1670a, Lanark County; 1660, Brudenell Township; 1681a, S. Burgess, Leeds County.

[b] Microliters per gram.

TABLE 2 – *Alpha-helium method intercalibration: alpha activity*

Sample	*Hurley* [1952]	*Hurley* and *Fairbairn* [1953]	*Hurley, Larsen,* and *Gottfried* [1955]	This work	Average for 1952–1953 + average for 1956–1957
	α/mg hr	α/mg hr	α/mg hr	α/mg hr	
1659	28	26	31	31.2 ± 0.7	0.87
1670a	51	52	68	...	0.76
1660	28	31	32	32.5 ± 0.7	0.91
1681a	35	36	32	32.7 ± 0.7	1.10
Average...					0.91

TABLE 3 – *Alpha-helium method intercalibration: apparent age*[a, c]

Sample	Source[a]	Source[b]	This work	Probable geologic age[a]
	m y	m y	m y	m y
Ontario				
1659.....	800	740	860 ± 50	1030
1670a.....	910	700	900[d] ± 50	1030
1660.....	740	680	890 ± 50	1030
1681a.....	600	660	670 ± 40	1030
Ceylon				
3002.....	...	480	560[d] ± 35	560
3027.....	...	440	500[d] ± 25	560

[a] *Hurley* [1952]; *Hurley* and *Fairbairn* [1953].

[b] *Hurley, Larsen,* and *Gottfried* [1955].

[c] All ages determined graphically (Fig. 3) from data in Tables 1 and 2.

[d] Calculated from the author's helium determination and alpha activities determined by *Hurley, Larsen,* and *Gottfried* [1956].

Table 3 compares the apparent geologic ages of these samples as determined at different times. The present results indicate retentivities varying from 60 to 100 pct for these samples rather than the previous seemingly more uniform three-quarters retention of helium.

Zircons from Oklahoma were also investigated (provided by D. Gottfried, U.S.G.S.). It is interesting that the metamict zircons (M15 and Z63) retain only a very small fraction of their radiogenic helium whereas the non-metamict zircon (NM15) has a much higher apparent retentivity. These zircon fractions are not pure; the fresh zircon contains some isotropic and weakly birefracting material, whereas the metamict zircon does not consist of pure isotropic crystal fragments but contains some weakly birefracting and some fresh zircon. If the relative amounts of impurity are known, the actual retentivity of pure isotropic and fresh zircon can be estimated. As can be seen (Table 4) a small amount of isotropic material is sufficient to lower significantly the apparent retentivity of fresh zircon since it will contain such a high concentration of uranium and thorium but will have lost most of the helium. This demonstrates the importance of working with pure unmetamict zircon, if accurate ages are to be determined by this method. It also suggests the effect of an inhomogeneous distribution of uranium and thorium within a crystal subject to metamictization.

TABLE 4 – *Alpha-Helium Ages for Oklahoma and North Carolina Zircons*

Sample	Activity	Helium	Apparent age
	α/mg hr	μl/gm	m y
Oklahoma NM15 (fresh)	187±4 189±4[a]	22.5 ±0.7	360±15
Oklahoma M15 (metamict)	1175±23	3.30±0.10	8.8±0.3
Oklahoma Z63 (metamict)	1110±40	4.50±0.23	12.3±0.9
Oklahoma NM15[b] (fresh corrected)	129	23.6	540
Oklahoma M15[b] (metamict corrected)	1290	1.0	2
Henderson County, North Carolina	246±5 240±5[a]	17.8 ±0.5	220±8

[a] Washed in aqua regia at room temperature for several hours.

[b] Values calculated assuming approximately five per cent metamict zircon in fresh fraction and 10% fresh in metamict fraction [*Larsen, Waring,* and *Berman,* 1953].

The 64-pct retentivity of the Henderson County, N. C., zircon (Tables 4 and 5) is based upon the age of Spruce Pine pegmatites. The sample was clean, non-metamict and washing in aqua regia (room temperature) did not significantly change the alpha activity.

A theory, based upon optical and x-ray evidence has been recently proposed by Holland, [*Holland* and *Gottfried,* 1955] to account for the effect of nuclear radiation on the structure of zircon. The theory envisages a four-stage process in which the structure is first saturated with displacements followed by the breakdown of the saturated lattice into crystallites of ordered zircon which ultimately breaks down into a $ZrSiO_4$ glass.

It is a matter of common knowledge that helium is able to diffuse through glass (this is a possible source of error in the determination of the helium content of minerals and is one of the reasons for blank and mock helium determinations), and *Keevil* [1941, p. 57] has shown that rocks with a glassy or cryptocrystalline ground-mass have extremely low retentivities compared to other rocks (31 porphyries and glassy lavas, most probable retentivity = 4.5 pct, mean value = 9.4 pct). Therefore, it would be expected that the existence of an extensive glass phase as a consequence of metamictization would also result in very low zircon retentivity. Ceylon zircons (Table 3) have a uniformly high retentivity (90–100 pct) up to a total irradiation of 0.565×10^{16} alphas per mg, but at 0.920×10^{16} alphas per mg total irradiation the retentivity is only about 26 pct. At 0.618×10^{16} alphas per mg total irradiation, metamict Oklahoma zircon has retained almost no helium. According to Holland and Gottfried, 0.618×10^{16} alphas per mg total irradiation corresponds to about 60 pct of the glass phase.

That the concentration of glass phase does not account entirely for the observed leakage is evident from the results on the Ontario zircons (Table 5). Three of these zircons have retentivities of about 80 pct, whereas the fourth has retained only about 60 pct of its radiogenic helium. Furthermore, according to the results of Holland and Gottfried, the total irradiation of these zircons is insufficient to result in the formation of a glass phase or the nucleation of a significant crystallite phase. If this is true, it is evident that some leakage may occur even in a completely undamaged crystal. The extent of this effect would be dependent on the degree of perfection of the original crystal, the extent of ionic substitution, and the subsequent thermal history.

TABLE 5 – *Apparent retentivity versus total irradiation*[a]

Sample	Total irradiation 10^{16} a/mg	Retentivity
Ontario 1659	0.027	0.81
Ontario 1670a	0.060	0.84
Ontario 1660	0.028	0.83
Ontario 1681a	0.029	0.61
Ceylon 3031	0.088	0.90[b]
Ceylon 3002	0.197	1.00
Ceylon 3027	0.565	0.90
Ceylon 3038	0.920	0.26[b]
Oklahoma (fresh)	0.099	~0.86[c]
Oklahoma (metamict)	0.618	~0.01[c]
Henderson Co., N. C.	0.076	0.64

[a] Ages assumed for reference: Ceylon, 560 m y [*Gottfried, Senftle,* and *Waring,* 1956]; Oklahoma, 600 m y [*Larsen, Waring,* and *Berman,* 1953; also G. Tilton, personal communication]; Henderson Co., N. C., 350 (?) m y [*Eckelmann* and *Kulp,* 1957]; Ontario, 1000 m y [*Eckelmann* and *Kulp,* 1957].

[b] Helium content from *Hurley, Larsen,* and *Gottfried* [1955] multiplied by the correction factor 1.16 derived from the data of Table 1.

[c] Corrected for purity (see Table 4)

In conclusion, the results of the present investigation indicate a higher retentivity relative to previous work for non-metamict zircons. The existence of more than about 50 pct of the glass phase due to radiation damage results in very low retentivities. Further study of the helium retentivity of zircon should yield information concerning the existence and extension of the permeable glass phase.

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Report of the Committee on the Upper Atmosphere

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Previous reports of the Committee summarized progress in research on the upper atmosphere up to the year 1952 [*Kellogg*, 1951, 1953]. Since that time additional rocket soundings, new and improved sounding techniques, and synoptic studies at higher levels have contributed additional knowledge which is summarized here.

It is hoped that the present summary will serve to 'clear the decks' until the greatly increased amount of upper atmosphere data to be collected more frequently and at many more stations during the International Geophysical Year becomes available. These data should yield the next large increase in our knowledge of the structure, composition and motions of the atmosphere above the tropopause and of the energetic radiations and particles which impinge on it.

We shall discuss first that portion of the stratosphere (below 30 km) which has been explored mainly by sounding balloons and then the atmosphere above 30 km which has been investigated mainly by rocket, acoustic and radio techniques.

The stratosphere below 30 kilometers

Pressure and temperature patterns—The average ceiling of meteorological sounding balloons has increased sufficiently in recent years to make practical a daily analysis of northern hemisphere weather charts at 50 mb (roughly 20 km). A series of such maps, carried out for seven months during 1953, has revealed the existence of slow-moving large cyclones and anticyclones, not always associated with tropospheric systems, and possessing well-marked thermal contrasts caused mainly by large-scale vertical motions [*Wexler* and *Moreland*, in preparation]. These contrasts reach their maximum in the late winter and early spring and are believed to account for the sudden 'Berlin-type warmings' observed in 1951, 1952, 1954, 1957 [*Scrase*, 1953; *Scherhag*, 1952; *Wexler*, 1956; *Warnecke*, 1956; *Craig* and *Hering*, 1957].

Prediction—At the 100-mb surface, where radiosonde data are more abundant, numerical prediction techniques were employed to make 24-hr barotropic forecasts for a period of 30 consecutive days in 1955 [*Arnason*, 1955]. The errors are comparable to those at the 500-mb level but, because of the smaller observed changes at 100 mb, the results are less useful than at 500 mb.

Ozone and water vapor observations—Development of ozonesondes is going on in the United States and in Europe. Three vertical ozone profiles made by A. W. Brewer in Great Britain in April and May 1957 show a marked stratification quite similar to that of water vapor observed on three occasions in the U. S. by *Barrett* and others [1950], but which have not been verified by the extensive water-vapor profiles observed by *Dobson* and *Brewer* [1951] and their associates.

Attempts to measure the vertical distribution of ozone from the ground by using infrared and ultraviolet ozone absorption bands were reported [*Epstein* and others, 1956]. Monthly mean values of 'effective radiation temperature of the ozone region' varies from $-32°$ to $-36°$ C in summer, to about $-44°$ C in winter. According to these measurements, seasonal variation of the vertical ozone distribution shows more ozone in lower levels in winter, but more ozone above 30 km in summer than in winter.

Stratospheric meridional circulation models—The recent discussion on stratospheric storage and mixing of Strontium^{90} has focused attention on stratospheric circulation models along meridians. A number of such models has been proposed by *Wulf* [1940], *Brewer* [1949], *Kellogg* and *Schilling* [1951], *Goldie* [1950, 1953]; and *Palmer* [1954]. Those of the British meteorologists which call for a tropospheric-stratospheric exchange appear to fit best the observed meridional distribution of Strontium^{90} fallout, ozone and water vapor.

The atmosphere above 30 kilometers

Winds—Following the earlier work of *Crary* [1952, 1953, 1954], an extensive set of data on the atmospheric flow at 30 to 60 km has been obtained by the University of Denver by observing propagation of sound from surface explosions. The experiments were conducted in Colorado, at intervals from July 1950 through August 1952. Results, reported by *Kennedy* and others [1955], indicate a tendency for the wind vector to move clockwise as the seasons advance, with strong west winds in winter, relatively weak east winds in summer. Measurements in October 1952 indicated a diurnal change, with temperature increasing as the winds decreased with the advance of the time of day through the daylight hours. Minimum temperatures and maximum winds generally occurred about 10h 00m MST.

This part of the atmosphere has also been observed by the Signal Corps with special high altitude balloons (up to 40 km) at Belmar, New Jersey, and with rockets equipped with grenades at White Sands, New Mexico, (up to about 80 km), the sound waves from which were observed at the ground [*Brasefield*, 1954; *Weisner*, 1956; *Stroud* and others, 1956; *Conover* and *Wentzien*, 1955]. The same annual change as reported above was observed. In winter the winds were westerly all the way up, with a maximum just below the tropopause, a minimum at about 25 km, and a gradual increase again to a broad maximum at about 50 to 60 km. In summer the easterly winds increased with altitude above 20 km, and reached a maximum at about 55 km. In August 1954, and again in January 1955, a special series of daily

ascents at four stations in a north-south line showed remarkably steady east winds at the 30-km level in August, but decreasing in speed with increasing latitude [*Lowenthal* and *Arnold*, 1955; *Kochanski*, 1956]. In January the winds had an average west component at this level, but showed great variability at all four stations.

A method of observation of winds in the 30 to 60 km region by rockets using directional pressure-sensing devices to relate the relative motion of the rocket through the air to its true trajectory has been reported by *Reisig* [1956]. A significant feature of such observations on three rocket flights was the very large shears observed in the mesosphere. These shears are comparable to those reported by *Whipple* [1953] from the observations of the drift of a meteor train at 80 to 90 km.

The winds in the ionosphere can be deduced from observations of the motion of irregularities in the ionization. A number of radio techniques have been used to measure the motion, such as the Doppler shift of radio echoes from meteor trains [*Manning* and others, 1952; *Greenhow*, 1952, 1954; *Elford* and *Robertson*, 1953], the reception of radio echoes from the ionosphere at several stations spaced about the transmitter [*Phillips*, 1952; *Yerg*, 1956]; and by the observation of the fadings of radio stars by a network of spaced receivers [*Wild* and *Roberts*, 1956], though in this case there is some question at certain times of day about the height of the irregularities that cause the moving pattern at the ground, since obviously the radio waves must pass through the entire ionosphere.

These various ionospheric observations have been summarized by *Kallmann* (1954], *Weekes* [1954], *Lovell* [1956], *Ratcliffe* [1956], and *Pant* [1956]. Some of the features which appear to emerge from them are as follows: In the meteor region from 80 to 100 km, the winds are predominantly from the east in summer, from the west in winter, with a measurable semidiurnal tidal component; in the E-region at about 110 km the mean drift is east in winter and west in summer, and there is a more pronounced semi-diurnal tidal variation, especially in winter.

Standard atmosphere—A new extension to the standard atmosphere was agreed upon by about 25 organizations in the United States. The basic data have been published in many journals (for example, *Wexler* and *Sissenwine* [1956]). The ICAO atmosphere was adopted as the standard for the lower 20 km of the atmosphere. A temperature maximum of 282.66° K was adopted for the region from 47 to 53 geopotential km and a minimum temperature of 196.86° K was chosen for the region from 75 to 90 geopotential km. The temperature then increases to over 1000° K at 300 geopotential km.

Aurora—Meredith and others [1955] have conducted experiments in recent years, examining the soft particle radiation coming in above 60 km at high latitudes, and undoubtedly associated with aurora. During cosmic radiation experiments being performed at high latitudes, a soft component of radiation was observed above the cosmic radiation plateau. This radiation penetrated in part to an altitude of 60 km, although absorption was present at least as high as 100 km. Careful measurements of this radiation have shown that most of it is x-radiation [*Van Allen* and *Kasper*, 1956]. It is apparently due to Bremstrahlung radiation from auroral electrons.

Airglow—Photometers have been carried in rockets to altitudes above those where the principal radiations of the night airglow are emitted. The oxygen green line at 5577 A, the sodium D lines at 5893 A and the continuous background at 5200 A and 5300 A have been examined. According to *Koomen*, *Scolnik*, and *Tousey* [1956], the continuous emission on the night of December 12, 1955, was concentrated between 90 and 110 km, with the strongest emission near 100 km. There was no emission apparent between 105 and 140 km, and about one-third of the radiation came from an altitude of above 140 km; this latter component may have been of extraterrestrial origin. They also indicate that the oxygen radiation occurs between 90 and 110 km, centered at 95 km, and that the sodium radiation occurs between 80 and 95 km, centered at 85 km. According to *Berg*, *Koomen*, and others [1956], the continuous radiation on the night of November 12, 1955, was slightly more spread out, with some concentration at 95 km and about one-half of the total energy emitted above 115 km. The oxygen green line was found to be emitted between 80 and 100 km, and centered at about 90 km, or slightly lower than found by Koomen and his colleagues.

Berg [1955] made photographic observations of the day airglow from a Viking rocket. He found no emission above 80 km, and the sensitivity of his system was such that brightnesses greater than 0.0075 candles ft^{-2} would have been detectable. This is much lower than the figures given by *Miley* and others [1953] and by *Bedinger* [1954].

Successful efforts for artificial production of night airglow by release of material from rockets fired at night were reported by *Bedinger* and others [1956] and by *Pressman* and others [1956]. Bedinger and collaborators released sodium vapor over the altitude range 50 to 113 km in April 1956 by burning sodium pellets in a thermite pyrotechnic. The trail was white from 78 to 95 km, and yellow from 95 to 110 km. The yellow light was fifteen times as strong as the normal skylight, and lasted about 15 minutes. Pressman and collaborators reported on emissions produced by the release of nitric oxide at an altitude of 106 km at night in March 1956. A strong luminous glow persisted for ten minutes. It is not clear whether the nitric oxide acted as a catalyst for the recombination of atomic oxygen, making the oxygen the energy source for the luminosity, or whether the nitric oxide was actually consumed by combining with atomic nitrogen to form molecular nitrogen and atomic oxygen.

Atmospheric density—The results of *Byram* and others [1956], based on absorption of solar x-rays in the upper atmosphere, have consistently indicated lower densities than those given by the *Rocket Panel* [1952], by a factor of about three from 110 to 128 km, and somewhat less at higher levels. *Horowitz* and *LaGow* [1957] have recomputed the densities and pressures measured during the flight of the Viking 7 rocket on August 7, 1951. Although the earlier computations from these measurements were in general agreement with the results published by the Rocket Panel, the new values agree well with those of Byram and his

colleagues, and with the distribution published by *Johnson* [1956].

LaGow and *Ainsworth* [1956] made pressure and density measurements at high latitudes and at altitudes up to 70 km and found pressures and densities only slightly larger than the values published by the *Rocket Panel* [1952] for White Sands, New Mexico.

Radio observations of whistlers, atmospheric disturbances which are propagated between the northern and southern hemispheres along magnetic lines of force extending as far as an Earth's diameter out from the Earth's surface, have provided an indication of densities in a region otherwise inaccessible to observation [*Storey*, 1953]. These indicate an ion density of about 600 cm^{-3}, a considerably higher value than was expected prior to these observations. It also makes clear the fact that the exponential decrease of atmospheric density does not approach zero, but instead that it approaches the above value, which is probably characteristic of the Sun's atmosphere near the Earth.

Atmospheric composition—Mass spectrometers have been flown in rockets to determine the ion and neutral particle composition of the atmosphere above 100 km. Neutral particle spectrometers were flown by *Townsend* and others [1954] on February 12, 1953, and by *Meadows* and *Townsend* [1956] on December 12, 1955. In the first experiment all mass numbers from 12 to 19, from 25 to 32, and from 38 to 44, all inclusive, were resolved. There was evidence that the observations were contaminated by rocket gas. No evidence of diffusive separation of nitrogen and argon was found in the region between 96 and 137 km where the observations were made. In the second experiment contamination was apparently not present and the following identifications were made: nitrous oxide and carbon dioxide at mass number 44, argon at 40, oxygen at 32 and 16, nitrogen at 28 and 14, and water at 18, also nitrogen dioxide at 46, and sodium at 23. No comment was made in the initial report concerning diffusive separation.

Johnson and *Heppner* [1956, 1955] have flown positive and negative ion mass-spectrometers in rockets and made measurements between 93 and 131 km on November 29, 1955 and between 100 and 120 km on July 8, 1955. On the flight of November 29, 1955, which was during the day time, no positive ions were observed but negative ions were observed at mass numbers 46, 32, 29, 22, and 16 with abundances 96.5, 1.06, 0.2, 1.0 and 0.7 per cent respectively. The identifications are NO_2^-, O_2^-, and O^- for mass numbers 46, 32, and 16 with numbers 29 and 22 not identified. On the earlier flights of July 8, 1955, made at night, no negative ions were observed, but mass 28 was observed in the positive ion spectrometer. This might be N_2^+, as suggested by Johnson and Heppner, or Si^+, as suggested by Havens. Still earlier, on a daytime flight in Viking X on May 7, 1954, a large number of positive ions were observed by *Johnson* and *Meadows* [1955]. On that occasion the rocket had a negative charge of up to 20 volts on it, which apparently made the experiment very effective for collecting positive ions. Hanson (private communication, 1956) has suggested that the results of Johnson and Heppner, obtaining positive ions but no negative ions at night, and negative but no positive ions in the daytime, might be due to weak charges on the rocket repelling the ions not observed. The positive charge during the daytime would probably be due to photoelectric effect, and the negative charge at night would probably be due to the greater mobility of electrons over positive ions acted on by the radio frequency field around the rocket. The Viking rocket from which the large number of positive ions were observed carried a powerful radio propagation experiment.

Some rather direct data bearing on the dissociation of oxygen in the upper atmosphere have been obtained by *Byram* and others [1955] using photon counters. The amount of molecular oxygen above the rocket was monitored by means of counters sensitive in the 1400 A region, while the total amount of atmosphere above the rocket was monitored with photon counters sensitive in the x-ray region. Comparison of the two results makes it possible to specify the degree of dissociation for oxygen. They find 50 pct dissociation at 112 km and about 70 pct dissociation at 130 km. These values are not in agreement with photo chemical equilibrium and have to be examined in the light of the studies by *Nicolet* and *Mange* [1954], which show that mixing plays an important role in establishing the oxygen distribution in the region where dissociation occurs. Above 150 km or so, it is possible that the oxygen distribution follows a diffusive law.

Meteors—A recent experiment of *Berg* and *Meredith* [1956] observes meteors by the flashes they make on striking a transparent surface in front of a photo cell. Impacts at the rate of 1 cm^{-2} min^{-1} were observed above 85 km, and this is near the upper limit of the values which have been predicted. An unexpected aspect of this result is the frequent penetration to a depth of 85 km, which implies that the meteors observed are considerably larger than one micron, the size generally supposed to be the most common, or that the velocities are much lower than the average meteor velocities, for example, about 12 km sec^{-1} instead of the 40 km sec^{-1} frequently assumed to be a good average. The latter possibility is the more attractive, since the small meteors can be expected to travel about the sun in nearly circular paths, and those which fall into the earth should do so with only slightly over the escape velocity, which is 11.2 km sec^{-1}.

Atmospheric light scattering measurements [*Bigg*, 1956] showed regions of dust accumulation below 20 km which were well correlated with radiosonde inversion measurements. Variations in scatter above 40 km suggest dust in varying amounts with maxima near times of known meteor showers.

Solar radiation—Several spectra of the sun have been photographed below 2000 A from altitudes above 100 km [*Johnson* and others, 1955; *Müller* and others, 1956; *Jursa* and others, 1955]. The end of the solar continuum and the change of the spectrum to an emission line spectrum is observed in this region. The shortest line photographed is a C III line at 977 A.

At wave lengths too short to photograph, photon counters have been used by *Byram* and others [1956]. They have made observations of the soft x-rays (8 to 100 A), which form the E region of the ionosphere, and they find an energy flux of about 0.01 microwatt cm^{-2}. The radiation absorbed in the F region, which falls in the wavelength range 100 to 900 A, has not yet

been observed, but will probably be measured as rocket altitudes increase sufficiently to carry instrumentation regularly into this region. Hard x-rays, with wave lengths from 4 to 10 A, probably cause the enhancement of the D region associated with radio fadeouts. *Friedman* [1956] observed a very pronounced enhancement of hard x-rays near 5 A which was associated with a solar flare which caused a mild radio fadeout. The Lyman alpha radiation from hydrogen, which is probably responsible for the normal D region, has now been measured on many occasions and the probability exists that it is not as variable as once thought. It has a value near 0.1 microwatt cm^{-2}; all the observed values fall within one order of magnitude of this value, and the experimental errors scarcely rule out the possibility of the value being constant.

Cosmic radiation—Studies of the cosmic radiation intensity distribution have led *Simpson* and others [1956] to believe that the geomagnetic field at high altitudes is only poorly indicated by the field at the Earth's surface. The data indicate that the field of the inclined dipole which approximates the Earth's field must be rotated by 40 or 45° to the west without any appreciable change in its inclination.

A spectacular increase in cosmic radiation intensity was observed in connection with a solar flare on February 23, 1956. Although a few similar occurrences have been observed previously, this outbreak was the best documented, and will surely yield the greatest amount of information on the relationship between cosmic radiation and the Sun. A paper by *Meyer* and others [1956] shows some of the observations which were made during this flare, and presents some interesting ideas concerning the mechanisms involved.

Ionosphere—The most interesting development concerning the ionosphere during the past few years has been the abandonment of the idea of discrete layers in favor of a continuous region of ionization. The different ionospheric 'layers' are now considered to be regions in which the electron concentration undergoes a relatively larger increase with height than in the remaining portions of the ionosphere. These ideas are supported by rocket measurements of electron density [*Seddon* and others, 1954] and by theoretical models [*Havens* and others, 1954; *Kallman* 1956]. The rocket measurements also show that the true heights for the F regions are much less than the virtual heights; this feature is also shown in the ionospheric model of *Kallman* [1956].

There is increasing agreement as to the wave lengths for the solar radiation responsible for the different regions of the ionosphere, and these wavelength ranges were mentioned above in discussion of solar radiation.

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Letter to the Editor

Recent Volcanic Eruption in Belgian Congo

On August 1, 1957, at 18h 10m GMT a brief renewal of activity occurred in the area of the supposedly extinct group of volcanoes in eastern Belgian Congo. A small cinder and spatter cone a few tens of meters high spewing gas and lava was formed at a place called Mugogo, (1°22'S – 29°29'E, elevation about 2400 m) 11 km north of 'extinct' Volcano Visoke and 12 km west-northwest of 'extinct' Volcano Sabinyo. A lava flow about one kilometer long issued from the cone. The activity stopped, except for fumaroles, on August 3. (This information was mostly received from the Albert National Park.) Warning of an imminent eruption had been issued eight days beforehand by De Bremaecker, on the basis of the swarm of very shallow earthquakes recorded at the seismographic station of Rumangabo, 14 km from the eruption, operated jointly by the Institut pour la Recherche Scientifique en Afrique Centrale (IRSAC) and the National Parks of the Belgian Congo. In the memory of people this eruption is the first activity in the so-called 'extinct volcanoes' region.

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Discussion of "Frequency of Point and Areal Mean Rainfall Rates"

F. A. Huff and J. C. Neill

[*Trans.*, **37**, 679–681, 1956]

Herbert M. Corn (Upham, Porter-Urquhart Associated, Tegucigalpa, Honduras)—The studies presented by Huff and Neill are interesting statistical evaluations of time and areal distribution of warm-season precipitation. Knowledge of rainfall's structure and cyclic development is sorely deficient and investigations of the type presented in the paper are excellent approaches for the better understanding of this most common phenomenon.

It is unfortunate that only 19 storm samples were available for analyses. However, it is understood that the primary program was for the determination of the value of radar as a device for the measurement of rainfall and the time-areal distribution studies were by-product analyses. It is hoped the research will continue with larger numbers of storm samples being accumulated so that the average pattern trends indicated by the original program can be conclusively validated as representative.

Previous studies by *Jarvis* [1931], *Linsley* [1947], and *Hathaway* [1945] indicated a structural uniformity in the physical processes of precipitation. Further, similarities were observed between the appearance of storm intensities of one-hour durations and those of lesser periods. Additional research performed by the writer [*Corn*, 1955, 1956] and *Cox* [1955] showed that parallel reliabilities existed in the probable appearance of maximum subintensities in individual rainfalls.

The basic data used for the studies by the writer were the tabulation of short-time maximum intensity rainstorms by *Yarnell* [1935]. Most of the entries therein can be categorized as warm-season rainfalls with a time-intensity distribution pattern similar to the rains examined by the authors. They show a general tendency for strong, high-intensity bursts, usually of short duration and advanced pattern, that is, the peak intensities usually occur within the first 30 or 40 pct of the total storm time.

The first 60 rainstorms listed in the publication were selected as being representative of diverse geographical and topographical locations and nonhomogeneous climatic conditions. Therefore, it was believed evidence of pattern or time-intensity distribution similarities would be indicative of a morphological rigidity within precipitation process.

Incremental maximum-period precipitation data were used for the studies in order to eliminate

differences that might appear due to the variations of pattern. Converting the incremental depths to percentages of total rainfall and plotting them against the intermediate periods expressed as percentages of storm durations, a time distribution curve of most-intense point rainfall was developed. The curve was similar to the one obtained by the authors (Fig. 2).

Comparison of the mean maximum precipitation curve of the writer and the time distribution curve of the authors indicate some quantitative differences. The latter curve shows that ten per cent of the rainfall occurred in approximately one per cent of the storm duration, 50 pct occurring in about ten per cent of the total storm time and 90 pct falling in 50 pct of the rain duration. The former studies indicated that an average of ten per cent, 50 and 90 pct of the total rainfall could be expected to occur within a period of approximately 4, 25, and 80 pct of the total storm duration.

The displacement of parameter positions, probably is due to the differences in magnitude of samples used for the separate studies. Recent re-examination of the sixty storms used for this writer's studies shows that one storm of June 21, 1933, at Burlington, Vermont, conforms fairly well with the time distribution curve of the authors. In this case, 50 and 90 pct of the rain fell in 6 and 45 pct of the total storm duration as compared to 10 and 50 pct indicated by the author's curve.

Since the particular rainfall was considered an extreme condition, when compared with the other 59 storms studied by the writer, it was considered as having little influence on the total picture and consequently disregarded as an important factor in the analyses. It was, however, noted in a discussion by *Hershfield* and *Wilson* [1956] that although the storm did not fit it was characteristic of the rainfall regime for Burlington. In fact, the situation occurs, on the average, about once every three years. Therefore, it is apparent that the time distribution curve of the authors is representative of warm-season rainfall for Illinois and a similar conclusion may have resulted if the studies had been carried out in Vermont.

The comparisons noted cannot be considered conclusive, since it is realized that a small number of events, selected at random, may be observed to follow any given average trace. It also follows that by restricting the area of study or by increasing the number of study samples quantitative curve modification will result. The importance of the comparisons lies in the qualitative verification.

Additional studies of time-depth rainfall distribution by Cox, as noted above, were concerned with long-time continuous rains. The collection compiled by the *Corps of Engineers* [1946] were used for the investigation. Storm durations examined included those from 6 to 114 hr, generally covering central and eastern United States. The mean curve derived was typically shaped and similar to that for short-time precipitation. The position of the parameter differed as had been expected, for the shorter incremental periods, but agreed very closely for the periods greater than 40 pct of the total storm time.

Generally it was indicated that lesser proportional amounts of rainfall could be expected in the periods up to 40 pct of the total rainfall duration for the longer storms than the short rains. Beyond this point, on the average, similar proportional amounts may be expected to accumulate.

The paramount disclosure of these parallel studies is the indication of an orderly process in the mechanics of precipitation. Apparently the haphazard physical appearance and inconstancies of the time-depth distribution for the incremental periods are characteristic of the uniformity. Surely, someday rigid mathematical equations will be available for proper analyses.

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F. A. Huff and *J. C. Neill* (Illinois State Water Survey Division, Urbana, Ill.; Authors' closure)—The authors thank Corn for his comments on our paper, and for his review of existing information on

the time distribution of rainfall rates. We agree that the 19-storm sample is probably too small to define accurately the time distribution of rainfall rates. As pointed out in our paper, the tabulated data were available as a by-product of another study and the results were presented as an indication of the approximate distribution of warm-season rainfall rates in Illinois and the Mid-west. We point out, however, that each of the 19 storms was sampled in detail through the use of 50 recording rain-gages on a 100-sq mi area. Corn's study, utilizing data by *Yarnell* [1935], was based on 60 storms but was restricted to single samples from selected storms, occurring in several different climatic regions.

The magnitude of the reduction problem restricted use of more storms in our original analysis. However, at the present time we are utilizing the electronic data-reduction facilities at the University of Illinois to process more one-minute rainfall data, and hope to obtain a sufficient number of storm samples to define further the approximate relations presented in our paper.

With regard to the differences between Corn's mean maximum precipitation curve and our time distribution curve we have no conclusive explanation of the differences. Part of the differences, at least, can be attributed to sampling errors. Neither the 19-storm sample of the authors nor the 60-storm sample of Corn are probably adequate for an accurate definition of time distribution relations. The restriction of our analysis to Illinois data and strictly to warm-season thunderstorm activity may have been a contributing factor. The use of numerous observations from individual storms and the use of one-minute rainfall amounts instead of five-minute increments are other differences in technique which may have affected the results. The authors believe that the use of multiple samples from individual storms and one-minute amounts are superior to the employment of Yarnell's data for determining the average distribution of rainfall rates within a given climatic area.

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Discussion of "A Nomogram for Log-Normal Frequency Analysis"

L. L. WEISS

[*Trans.*, **38**, 33–37, 1957]

Ven Te Chow (University of Illinois, Urbana, Illinois)—The writer would like to mention another method for the determination of the log-normal amount, which uses a table of frequency factor.

The statistic variate X corresponding to any probability and any law of probability can be expressed by a general formula [*Chow*, 1951] as follows

$$X = \overline{X} + S_X K \tag{13}$$

in which K is a so-called frequency factor depending on the pattern of the frequency distribution of the variate. When the log-probability law is used, a table of the frequency factor has been prepared [*Chow*, 1954] and can be applied. Considering the example given by the author, the frequency factor for $C_s = 0.25$ and a probability of one per cent can be obtained from this table as $K = 2.88$. The corresponding log-normal amount by (13) is $3.48 + 0.88 \times 2.88 = 6.01$. This agrees with the value obtained by the author from the nomogram.

When the extreme-value law or the Gumbel distribution is applied, the frequency factor can be obtained from a K-T curve [*Chow*, 1951, Fig. 9]. Considering the example given by the author, the frequency factor for $T = 10$ yr and $n = 40$, the frequency factor from the K-T curve is $K = 1.48$. The corresponding extreme-value by (13) is $3.0 + 0.50 \times 1.48 = 3.74$. This agrees with the author's answer.

By means of (13), the ratio of the log-normal amount to that for the extreme-value of a particular return period may be written as, using author's notations

$$R_T = \frac{X_T}{X_{TG}} = \frac{1 + C_s K_L}{1 + C_s K_G} \tag{14}$$

in which K_L is the frequency factor for the log-probability law and K_G the frequency factor for the extreme-value law.

When $n = \infty$, it has been shown [*Chow*, 1954] that the log-probability law is practically identical

with the extreme-value law for $C_v = 0.364$. In other words, when $C_v = 0.364$, $K_L = K_G$ and (14) gives $K_T = 1$. This is not shown in Figure 3, but can be readily verified by the above method or by the author's nomograms.

Note that when an equation like (14) is used, the sample for the log-probability frequency analysis is the same sample for the extreme-value frequency analysis, and hence the period of record in both cases is equal to the same value n. The value of X_T as represented in (11) is based on a theoretical distribution of $n = \infty$. For a sample of limited size, however, X_T is also a function of n just as X_{TG} is a function of n. Since X_{TG} is made a function of n through the use of a plotting position formula containing n, it is possible that X_T is made a function of n by a similar procedure. Otherwise, a procedure developed by *Foster* [1955, Fig. A] is applicable for the development of X_T as a function of n. It seems to the writer that (12) is valid only if $n = \infty$ or if a correction for n is to be applied to X_T in (11) in the course of the derivation of (12).

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L. L. Weiss (U. S. Weather Bureau, Washington, D. C.; Author's closure)—I want to thank Chow for his discussion. It is gratifying to see the verification of my examples by his general method for frequency analysis. Since the use of his table of frequency factors or my nomogram give the same results, the choice is a matter of user preference.

With regard to Chow's interesting remarks in his concluding paragraph, I would leave moot the question of the dependence of the X_T on sample size. The comparison which I wanted to illustrate in Figure 3 was that between the values when computed in the usual fashion using sample mean and standard deviation. Nothing was said concerning the confidence bands for either method. If these are taken into account, we may say that for practical applications the differences between the values determined by the two methods are not important.

Discussion of "Frequency of Discharges from Ungaged Catchments"

by J. E. Nash

[*Trans.*, **37**, 719–725, 1956]

Ven Te Chow (University of Illinois, Urbana, Illinois, received April 26, 1957)—The author has developed an ingenious method to determine the frequency of peak discharge under the condition of several assumptions. In this method the frequency is calculated by a numerical procedure of finite summation. For a similar purpose, the writer has employed a procedure of graphical integration which will be demonstrated as follows.

The formula used by the writer for the determination of a peak discharge is

$$Q = CRP + Q_0 \tag{16}$$

in which C is a runoff coefficient depending on the soil type, antecedent watershed condition, land use, and intensity and duration of rainfall; R, the rainfall depth; P, the peak discharge of unit hydrograph depending on watershed slope, size, length, geographic and geologic conditions; and Q_0, the base flow. Since the purpose of this discussion is to show the procedure of graphical integration, the detailed procedure for determining C, R, P, and Q_0 will not be mentioned, and also Q_0 is assumed zero in the given example.

For an example, it is required to determine the frequency of a peak discharge of 500 cfs from a given watershed of 5.3 sq mi. In Table 2, column 1 gives the duration of rainfall in hours. Column 2 gives the peak discharge in cfs, of the unit hydrograph of a duration corresponding the value in column 1. Column 3 gives the rainfall excess in inches, or $CR = Q/P$, equal to 500 cfs divided by the value of P in column 2. Column 4 gives the rainfall depth obtained by dividing the value in column 3 by a pertinent runoff coefficient corresponding to the rainfall excess. The rainfall depth-

TABLE 2 – *Computation of the frequency of peak discharge*

T (1)	P (2)	CR (3)	R (4)	F_2 (5)	F_1 (6)	$F_2 - F_1$ (7)
0.5	1170	0.427	2.20	0.009	—	0.009
1.0	1133	0.443	2.20	0.030	0.009	0.021
1.5	1110	0.450	2.23	0.060	0.028	0.032
2.0	1060	0.471	2.25	0.092	0.057	0.035
2.5	1000	0.500	2.35	0.110	0.080	0.030
3.0	925	0.541	2.40	0.130	0.100	0.030
3.5	870	0.575	2.45	0.145	0.120	0.025
4.0	805	0.622	2.55	0.145	0.125	0.020
4.5	752	0.665	2.65	0.140	0.125	0.015
5.0	685	0.730	2.75	0.130	0.115	0.015
5.5	621	0.805	2.90	0.115	0.105	0.010
6.0	571	0.875	3.00	0.100	0.090	0.010
6.5	527	0.950	3.10	0.090	0.085	0.005
7.0	490	1.020	3.23	0.080	0.075	0.005
						$\Sigma = 0.262$

duration-frequency curves at the location of the watershed are shown in Figure 8. Columns 5 and 6 in Table 2 give the frequencies F_2 and F_1 respectively at the end $(T + h)$ and beginning $(T - h)$ of the duration interval ΔT. These frequencies are obtained from the curves in Figure 8. For $T = 1.5$ hr, as an example, the frequencies $F_2 = 0.060$ and $F_1 = 0.028$. The dashed line in Figure 8 shows how these frequencies for various durations are found. Column 7 in Table 2 gives the difference $F_2 - F_1$ or $F(R, T, O)$ as defined by (5). Consequently, according to (7), the sum of all values in column 7 should be equal to the frequency of 500 cfs as the peak discharge. This is found to be 0.262 or 3.8 yr.

Taking the rainfall depth R as a parameter, the curves in Figure 8 can be replotted with the frequency F against the duration T as shown in Figure 9. Also in Figure 9 are plotted the values

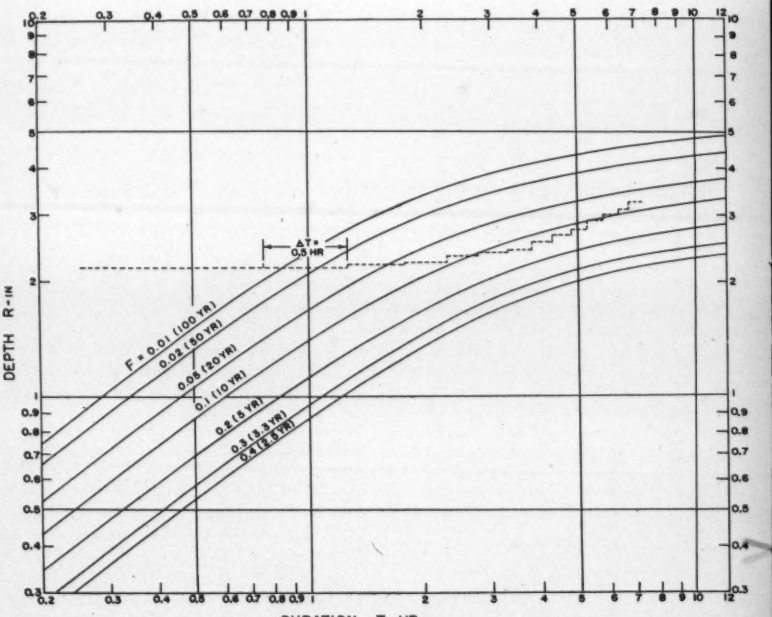

FIG. 8 – Rainfall depth-duration-frequency curves

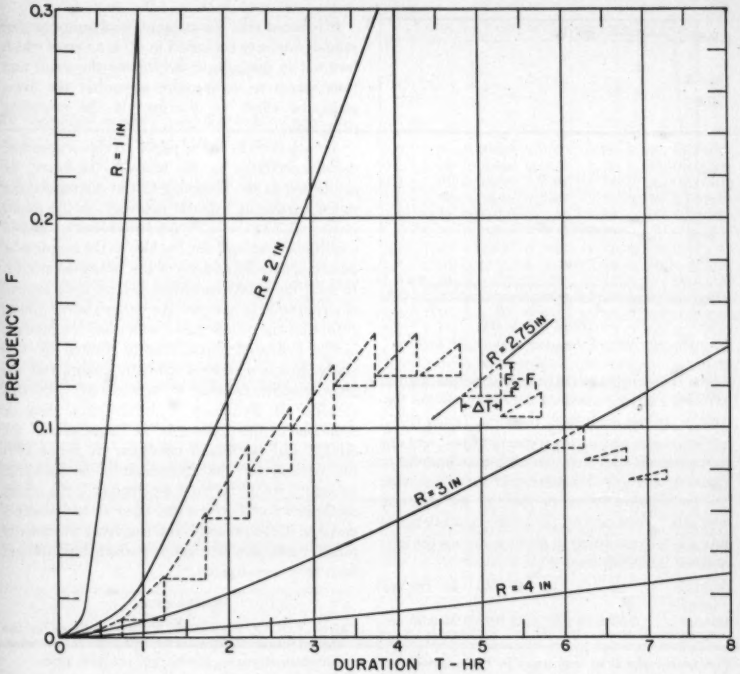

FIG. 9 – Plot of the relation of F to T

from Table 2 for $T \pm h$ against F_2 and F_1. For each duration interval, or 0.5 hr in the example, a right triangle shown in dashed line can be constructed. In this triangle, the vertical side represents $F_2 - F_1$, the horizontal side represents the duration interval $\Delta T = 0.5$ hr, and the hypotenuse has a slope equal to the slope of the solid line representing the rainfall depth R corresponding to the duration T. According to (7), the frequency of the peak discharge is equal to the sum of the lengths of all vertical sides of the triangles; that is

$$F_q = \sum_0^T (F_2 - F_1) \qquad (17)$$

or, expressed in the integral form

$$F_q = \int dF = \int (dF/dT)\, dT \qquad (18)$$

The term dF/dT represents the slope of the solid line in Figure 9. Taking the rainfall depth R as a parameter, this term dF/dT can be plotted against the duration T as shown in Figure 10.

Plot the duration T in column 1 of Table 2 against the rainfall R in column 4, resulting in a dashed curve in Figure 10. According to (18), it is apparent that the area under this curve should be equal to the frequency of the peak discharge. This area can be planimetered and is found to be 0.280 or 3.6 yr, which agrees satisfactorily with the result obtained by the numerical procedure in Table 2. In comparing the numerical procedure with the graphical procedure, it is obvious that the accuracy of the former depends on the magnitude of the duration interval ΔT or $2h$, whereas the accuracy of the latter depends much on the scale used for constructing the curves.

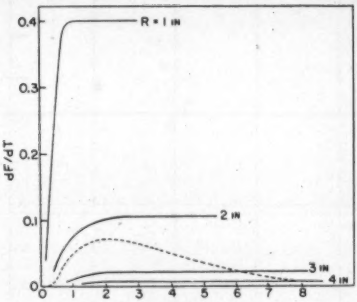

FIG. 10 – Plot of the relation of dF/dT to T

The writer believes that the Dillon data used in author's analysis tends to overestimate the frequency. In the analysis of the data, *Dillon* [1954] has followed a conventional concept that "any one storm can allow an entry for each time interval or duration, and any one portion of the storm-trace can be included in one or more of the duration intervals." For example, the amounts of rainfall of July 23, 1916 occurring in given durations (or less) as listed by Dillon are:

Duration (min)	10	15	30	45	60	90	120	etc.
Amount (inch)	0.50	0.65	0.91	0.94	0.95	0.96	0.98	etc.

The first value 0.50 was used in the analysis for $T = 10$ min or less, the second value of the same storm 0.65 was used in the analysis for $T = 15$ min or less, and so on. Thus, the effect of this storm has been included in the analyses of several durations; whereas the storm actually occurred only once and, in accordance with the implication of the author's method, it could produce only one independent discharge. In other words, this storm has been counted several times in the author's analysis and hence the resulting frequencies have been overestimated. If the actual duration of this storm is known, the storm should be counted or included in the analysis only once for this duration only. The curves as shown in Figure 8 were derived from an analysis based on this new concept. A comparison of these curves with the conventional curves indicates that the overestimation of the latter exists for durations less than 1.5 hr in the given example. For durations greater than 1.5 hr the overestimation is practically negligible.

It is noted that the assumption of uniformity of rainfall intensity contained in (2) is an error which fortunately tends to underestimate the result and thus serves to compensate somewhat the overestimated effect as described in the preceding paragraph.

Assumption (1) in the paper accepts a constant runoff coefficient in the analysis. However, as mentioned in the beginning of this discussion, the runoff coefficient depends not only on the major factors such as the soil type, antecedent watershed conditions, and land use, but also on the magnitude, duration, and distribution of the individual storms. In fact, the runoff coefficient is a variable instead of a constant. It has been the writer's belief [*Chow*, 1956] that the runoff from a watershed is a product in the hydrologic cycle that is affected by two major groups of factors: climatic factors and the physiographic factors. In accordance with this concept, the frequency of the discharge may be conceived as the product of the frequencies of the rainfall and the runoff condition. It seems that the method for the determination of discharge frequency would be more satisfactory if the runoff coefficient could be treated also as a statistical variable. Unfortunately, the frequency analysis of runoff coefficient is a subject which has not yet been fully investigated.

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J. P. Farrell (Office of Public Works, Engineers Branch, Dublin, Ireland, received May 2, 1957)—This paper fills a serious gap in the literature on the problem of relating runoff frequencies to rainfall frequencies. However the method set out by the author of applying the principle that "On a given catchment the frequency of q is the sum of the frequencies of all storms which cause q," where q is the peak discharge in cfs/mi^2 is somewhat complex and mistakes could easily creep in. The following alternative derivation and method of working may therefore be of interest.

As described by the author the ordinate at time t of the unit hydrograph for effective rainfall duration T may be derived from the instantaneous unit

hydrograph and is

$$U(T, t) = \frac{1}{T}\int_{t-T}^{t} U(0, t)\, dt$$

By choosing t so as to maximize this integral the peak of the unit hydrograph of period T is obtained. This latter peak may be denoted by P_T and the peak of the instantaneous unit hydrograph by P_0. A curve may then be plotted of P_0/P_T against T or to get ratios on both axes, of P_0/P_T against T/t_{P_0} where t_{P_0} is the time to peak of the instantaneous unit hydrograph. Such a curve derived from Commons basic hydrograph which the author used as his instantaneous unitgraph shape is shown by the full line in Figure 11. Curves derived in the same way from other well known unitgraphs are shown for comparison. If P_0 is the peak in cfs/mi² due to one inch instantaneously on the catchment, then ordinates of the curve give for any duration T of rainfall, the amount of rainfall in inches of that duration necessary to produce a peak equal to the instantaneous peak P_0. In other words, the curve shows all the rainfall combinations which could produce such peak. A plot of all the combinations to produce some other peak rP_0 will be got by multiplying all the P_0/P_T ordinates

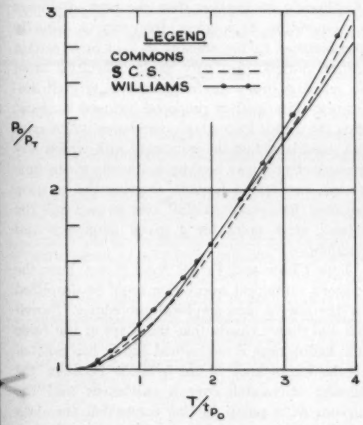

FIG. 11 – Depth-duration curves of rainfall to produce a peak equal to the instantaneous unitgraph peak from different unit graphs

TABLE 3 – *Example of frequency calculation*

T/tp₀ 1	P₀/P_T 2	T/tp₀ / (0.072 (P₀/P_T)³) 3	F(R,T,O) 4	T 5	μ 6	F(R,T,A) 7
0.0	1.00	0.00000	0.0000	0.00	0.000	0.00000
0.2	1.01	0.01368	0.0439	1.92	0.085	0.00373
0.4	1.03	0.02484	0.0797	3.84	0.121	0.00964
0.6	1.07	0.03074	0.0987	5.76	0.159	0.01569
0.8	1.12	0.03276	0.1052	7.68	0.195	0.02051
1.0	1.17	0.03283	0.1054	9.60	0.231	0.02435
1.2	1.25	0.02830	0.0908	11.52	0.260	0.02361
1.4	1.36	0.02167	0.0696	13.44	0.290	0.02018
1.6	1.48	0.01627	0.0522	15.36	0.320	0.01670
1.8	1.59	0.01260	0.0404	17.28	0.345	0.01394
2.0	1.70	0.01015	0.0326	19.20	0.380	0.01239
2.2	1.82	0.00792	0.0254	21.12	0.400	0.01016
2.4	1.93	0.00644	0.0207	23.04	0.430	0.00890
2.6	2.04	0.00530	0.0170	24.96	0.450	0.00765
2.8	2.15	0.00439	0.0141	26.88	0.470	0.00663
3.0	2.27	0.00357	0.0115	28.80	0.490	0.00564
3.2	2.38	0.00301	0.0097	30.72	0.500	0.00485
3.4	2.50	0.00251	0.0081	32.64	0.520	0.00421
3.6	2.61	0.00215	0.0069	34.56	0.540	0.00373
3.8	2.72	0.00182	0.0058	36.48	0.560	0.00325
4.0	2.83	0.00159	0.0051	38.40	0.580	0.00296
5.0	3.39	0.00080	0.0026	48.00	0.640	0.00166
6.0	3.95	0.00045	0.0014	57.60	0.690	0.00097
7.0	4.51	0.00027	0.0009	67.20	0.730	0.00066
8.0	5.07	0.00017	0.0005	76.80	0.770	0.00039
9.0	5.63	0.00012	0.0004	86.40	0.790	0.00032
10.0	6.19	0.00008	0.0003	96.00	0.820	0.00025

by r. According to Dillon's rainfall frequency formula used by the author the frequency of occurrence in times per year of R inches in T or less hours is equal to $0.036\ T^2/R^5$. This implies that the frequency of the (R, T) combination is measured by the first derivative $0.072\ T/R^5\, dT$ which is a function of position along the curve described above. It is the writer's suggestion that the frequency of q may be taken as the line integral of the function $0.072\ T/R^5$ along the curve showing all the rainfall combinations which could produce q, that is

$$F_q = \int 0.072\ T/R^5\, dT$$

Modified by the introduction of term μ used by the author to allow for the diminution in rainfall frequency with increasing area, the expression for the frequency of q becomes

$$F_q = \int 0.072\mu\ T/R^5\, dT$$

Values of T/R^5 taken from the curve can be calculated, multiplied by the appropriate values of μ listed by the author and plotted against T. The area between this last curve and the T axis then gives the required frequency. Since the rainfall of duration T to produce q is $R = q/P_T$, the rainfall frequency function $0.072\ T/R^5$ can be written in the form

$$\left[0.072\ \frac{T/t_{P_0}}{(P_0/P_T)^5}\right] \times \left[t_{P_0}\left(\frac{P_0}{q}\right)^5\right]$$

Once a rainfall frequency formula (such as Dillon's) has been selected, the quantity in the first large bracket above is purely a function of the instantaneous unitgraph shape being used and need be calculated only once. In the case of Commons' basic hydrograph 1200 volume units represent 645 ft^{3}hr/sec and 60 discharge units represent P_0 cfs also t_{P_0} equals 14 time units. Therefore $t_{P_0} = 451.5/P_0$ hours.

To exemplify the suggested method, the particular case of $P_0 = 47$ cfs/mi^2 corresponding to an area of 50 mi^2 and slope of 200 pct is worked out in Table 3 for a q of 74.7 cfs/mi^2. The frequency of other q's will of course be inversely proportional to q^6. Columns (1) and (2) in Table 3 are a tabulation of Figure 11. Column (3) derived from them is a function only of Commons' hydrograph and the rainfall frequency formula. Column (4) is the product of values in Column (3) by 3.21 which is the value of $[t_{P_0}(P_0/q)^5]$ in this case. To insert values of μ it is necessary to obtain absolute values of T from column (1) by multiplying the latter by 9.60 hr the value of t_{P_0} on this catchment. The final column consists of the products of columns (4) and (6) and is plotted as the full line in Figure 12 where it is described as $F(R, T, A)$. Fq is the area under this curve and amounts to 0.448 times/yr which is reasonably close to the value given by the author's chart. The curve which would be obtained by omission of the μ factor is plotted as a dotted line on the same diagram to the scale marked $F(R, T, O)$. Its very great effect can there be seen and it is most unfortunate that there is such a dearth of data of this type. Figure 11 demonstrates that there is practically no difference between these curves when derived from different unitgraphs. Hence the frequencies obtained with these unitgraphs will be proportional to their t_{P_0} values.

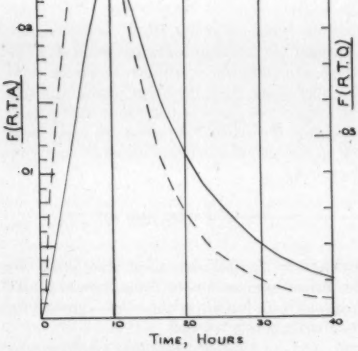

FIG. 12 – Frequency-duration curves of the rainfall combinations which can produce the given run off peak

J. E. Nash (Department of Scientific and Industrial Research, Hydraulics Research Station, Howbery Park, Wallingford, Berks, England; Author's closure)—The purpose of this paper was to draw attention to the fact that once one departed from Kuichling's assumption that the peak discharge corresponding to a given frequency is directly proportional to the amount of rain in a certain critical period, then very great difficulties arose in relating discharge frequency to rainfall frequency. The method proposed assumed as basic data (1) a unit hydrograph correlation, (2) a rainfall formula giving the frequency with which any amount of rain may be expected in any given time or less, and (3) a formula showing the relation between the average rainfall over an area and the rainfall at a point for a given frequency and duration.

Both Chow and Farrell have shown how the author's numerical calculation could be simplified by the use of semi-graphical procedures. Farrell has also shown clearly that the shape of the basic unit hydrograph is not critical and he has pointed to the importance of the relation between the amount of rainfall over a catchment and the amount at a point. In this connection the data used by the author, which are the only such data available for the British Isles, are very unsuitable. It is clear that very much progress cannot be made until reliable data on this point become available.

Chow has pointed to the overestimate involved in using Dillon's rainfall formula. He emphasizes the fact that Dillon's method of analysis, which is the standard one, permitted more than one entry for one storm, and the storm of July 23, 1916 provided a whole series of entries while, of course, providing in fact only one peak discharge. This is undoubtedly true but it is very easy to overestimate the effect of this multiple use of one storm. The storm of July 23, 1916 provided say seven entries but each of these entries corresponds to a different discharge. It does not follow, as one would perhaps conclude at first sight, that a certain discharge is overestimated six times. An example will make this clear.

Consider a catchment which is very small and very steep so much so that $U(O, P) = 300$ cfs/mi². This is indeed an extreme case. Suppose we are counting the occurrences of a discharge equal to or greater than 112 cfs/mi² and we used a runoff coefficient of 0.5 we therefore require 0.75 inch of rain instantaneously, or any of the following amounts in corresponding times:

Durations (min)	10	15	30	45	60	90	120
Amount (inch)	0.75	0.76	0.76	0.77	0.80	0.83	0.91

Our analysis is equivalent to approaching each storm in the record and adding up (1) the number of occurrences of 0.91 inch, or more, in 120 min less the number of occurrences of 0.91 inch or more in 90 min, namely, $F(R, T + h, A) - F(R, T - h, A)$ plus (2) the number of occurrences of 0.83 inch, or more, in 90 min less the number of occurrences of 0.83 inch, or more, in 60 min plus (3) the number of occurrences of 0.80 inch, or more, in 60 min less the number of occurrences of 0.80 inch, or more, in 45 min plus (4) the number of occurrences of 0.77 inch, or more, in 45 min less the number of occurrences of 0.77 inch, or more, in 30 min plus (5) the number of occurrences of 0.76 inch, or more, in 30 min less the number of occurrences of 0.76 inch, or more, in 15 min plus (6) the number of occurrences of 0.76 inch, or more, in 15 min less the number of occurrences of 0.76 inch, or more, in 10 min.

Now (1)(2)(3)(4) furnish one minus one occurrence each, (5) furnishes one minus zero occurrence, (6) (and any subsequent) furnishes zero minus zero occurrences. Consequently our analysis takes only one occurrence equal to or greater than 112 cfs/mi² from this storm on a catchment of $U(O, P) = 300$ cfs/mi².

If we consider the number of occurrences of other discharges provided by this storm we shall always find that not more than one period will provide one minus zero occurrence. All the other periods will provide either one minus one or zero minus zero occurrences. The period which provides one minus zero occurrences will vary depending on the magnitude of the discharge whose frequency is being investigated, the higher the discharge the longer the period which proves critical.

For any other catchment where $U(O, P)$ is not greater than 300 cfs/mi² a similar result will be obtained. If $U(O, P)$ is taken very much greater than this it is possible that more than one occurrence will be registered. However such a catchment would be entirely outside the range visualized in this paper. It is possible however that a storm of greater duration than that of the July 23, 1916 would register two or more occurrences of a chosen discharge, even on a more moderate catchment and we must therefore accept the possibility of some overestimation. It would appear however to be very much less than would at first sight be expected.

There appears to be no way of eliminating this difficulty except by a radically different approach to the rainfall analysis. Chow mentions an analysis in which any storm is allowed to produce one entry only (namely, the amount of the storm in the total duration of the storm). This however raises further difficulties. Consider a rain storm containing a short break in its center, such a storm might produce two distinct peak discharges on a small catchment and possibly only one peak discharge on a large catchment. It would be desirable therefore, when preparing the rainfall frequency formula, to consider this storm as two storms when considering small catchments and as one storm when considering large catchments. This would require a different analysis for each different catchment.

Discussion of "A Treatment of Self-Gravitational Strains in the Earth"

WILMOT R. MCCUTCHEN

[*Trans.*, **38**, 95–98, 1957]

Jean Goguel (Service de la Carte Géologique, Paris, France)—It is not so much the treatment of this problem by Wilmot R. McCutchen that I want to discuss (also the replacement of Eq. (6) by Eq. (5) does not seem to be correct), as the very principal of the problem.

Mathematical theory of elasticity supposes that there is a 'natural state,' with no stress, and no external forces. From there, it allows the computation of stresses and strains involved when the external forces are applied. But, in the case of the Earth, this 'natural state' has no physical sense. It would mean that the Earth was built up with no gravitation, and was then devoid of stress, and that afterwards, gravitation was applied. It is quite certain, on the contrary, that the Earth was affected by gravitation from the beginning.

As we do not know how the Earth was built up, it does not seem possible to compute how stresses developed during its evolution.

But it can be assumed that each elemental volume which was affected by a non-hydrostatic stress had to yield by some sort of creep in such a way that the stresses tend toward an hydrostatic pressure. The mathematical study of the relaxation of stress caused by such a creep enables us to compute the final state of stress [*Goguel*, 1942ab, 1943]. But, in the case of the Earth, it can be readily seen that the stresses caused by the permanent forces must have an hydrostatic character. Of course, temporary stresses and strains, as for instance, in the propagation of seismic waves, or in tides, obey the ordinary equations of elasticity.

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Wilmot R. McCutchen (U. S. Army War College, Carlisle Barracks, Pa.; Author's closure)—The theory of elasticity can be applied to the study of materials subject to body or gravity forces as well as external forces. Problems such as the extension of a suspended rod due to its own weight, the shortening of a column from the same cause, or the deflection of a beam due to dead load may be cited as examples. These problems all suppose an undeformed state as a point of reference. Strictly speaking, this state would have no more of a physical sense than the undeformed body of the Earth, inasmuch as the weight of any body has always been present. Nevertheless, the undeformed state is a useful concept in the evaluation of strains induced by body forces.

It should perhaps be re-emphasized that the strains were derived initially from the configuration of the body and quite apart from any consideration of the stress state. The resultant stress state may be either hydrostatic in nature or one with stress differences. As Goguel observes, it is probable that stresses in the mantle would tend to be more equalized than the stress state to be expected in a perfectly elastic medium. We found, however, that the strain equation has the same form for either stress state, if we disregard a term involving a product of differentials. For this reason, we need to question only the assumption that the primary seismic-wave velocity furnishes a measure of the stress to strain modulus through the range of strain values considered. Although these velocities are associated with transitory deformations, they are perhaps the best available evidence of the behavior of the Earth's material under stress. The method of using these seismic velocities to investigate static strain states was suggested some years ago by Adams and Williamson. It has found useful application in subsequent studies referenced in the paper.

Reviews, Abstracts, and Bibliography

Reviews and Abstracts

J. C. JAEGER, *Elasticity, fracture and flow, with engineering and geological applications*, John Wiley & Sons, 152 pp., 1956, $2.50.

This recent addition to the series of Methuen's Monographs on Physical Subjects brings together in a succinct form the basic theories and properties of the elastic, plastic, and viscous deformation of materials. The emphasis in the book is on the mathematical development of the concepts of stress and strain and on the various theories relating them, including the assumptions involved. The book is intended for engineers and geologists whose main interest is not in the methods of solution of special elastic, plastic, viscous, and rheological problems which comprise large portions of the text books covering these problems.

A fair understanding of the book is possible for a reader with a basic preparation in physics and elementary calculus, but it will be read more easily with a background of engineering strength of materials or of elasticity theory. A reader who is unfamiliar with the theory of elasticity can follow the derivations through without difficulty as the author has given all the essential equations. The book is amazingly comprehensive for its small size, principally because the author is concerned with basic considerations of theory and behavior of materials without pausing to elaborate on specific examples with lengthy mathematical expressions.

In the first of the three chapters in the book, the author gives fairly complete separate developments of the mechanics of stress and the geometry of strain, initially for two and then for three dimensions. Mohr's circle diagrams are discussed for the representation of stress and of strain.

The second chapter on the behavior of actual materials is a superb condensation in which quite appropriately the relations between stress and strain are developed. Hooke's Law is developed for a perfectly elastic isotropic solid, and applicable theories are developed for plastic and viscous materials. Adequate summary treatment is given the topics of anistropy, finite strain, and natural strain. A fairly thorough treatment is given the observations and the criteria of failure by fracture and flow. In a section at the end of the chapter, the author discusses in logical order the various theoretical models for the behavior of substances as a function of time, and these are made clear by the use of spring-and-dashpot mechanical models.

The third chapter is a collection of special topics including applications of equations from Chapters 1 and 2, and the derivation of equations in which both body and surface forces act on elastic, plastic, and viscous materials. For example, the author develops the equations of elasticity of a body in motion and then discusses the elastic waves and their applications to earthquake waves and seismic prospecting. The equations of motion of viscous fluids are introduced and examples treated; and the determination of slip lines in plastic flow are discussed.

In common with the other Methuen Monographs, this one has received careful editing and there are no obvious typographical mistakes. The author has chosen clear, simple line drawings to illustrate the text and has had some of the special topics printed in smaller type. Greek letter symbols for stress, strain, and various moduli have been used by the author, following current engineering practice; tensor notation is not presented. It would be helpful to those unfamiliar with engineering usage to have a list of the symbols and their definitions given at the beginning of the book.

A possible criticism even for such an abridged treatment is that the author has neglected pertinent thermodynamic theory; it is only fair to say that no other author has tried to apply thermodynamics to the problems of elasticity and plasticity, even though J. Willard Gibbs worked out the basic theory over 50 years ago. *MacDonald* [1957] in a recent recast of Gibbs' work has shown the fruitfulness of the thermodynamic approach to the geologic problem of flow of rocks. The restrictions on the theoretical treatments of elasticity and plasticity placed by thermodynamic theory provide a powerful tool for the further development of analysis of deformation of materials.

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Notes and Personalia

Notes

CORRECTION IN DEATH NOTICE CONCERNING HARALD ULRIK SVERDRUP—On pages 796–797 of the October 1957 issue of the *Transactions*, the death notice of Harald Ulrik Sverdrup indicated incorrectly his age and the date of his death. He was born on November 15, 1888, and this would make him 68 at the time of his death which occurred on August 21, 1957. He was Director of the Norwegian Polar Institute—not the North Polar Institute.

POSTHUMOUS AWARD TO CARL-GUSTAV ROSSBY—The Executive Committee of the World Meteorological Organization has awarded the annual prize, created to commemorate the International Metrological Organization, to Carl-Gustav Rossby, who died August 19, 1957.

SCIENCE FELLOWSHIPS OF THE NATIONAL SCIENCE FOUNDATION—The National Science Foundation has announced that applications are now being received in four National Science Foundation Fellowship Programs for advanced study and research in the natural sciences, as follows: (1) a predoctoral fellowship program for which college seniors and graduate science students may apply; (2) a postdoctoral fellowship program for scientists who have already received the doctoral degree; (3) a senior postdoctoral fellowship program for candidates who have held the science doctorate for a minimum of five years; and (4) a science faculty fellowship program for college teachers of science who wish to improve their competence as teachers. Approximately 1000 awards will be made in March, 1958. The closing dates for applications for the first two groups is December 23, 1957, and January 3, 1958, respectively; and for the third and fourth groups, January 13, 1958. Interested persons should write to the Fellowship Office, National Academy of Sciences, 2101 Constitution Avenue, N. W., Washington 25, D. C.

INSTITUTES FOR HIGH SCHOOL SCIENCE AND MATHEMATICS TEACHERS—The National Science Foundation has announced grants totaling $4,350,000 to 17 colleges and universities to support academic-year institutes designed to help high school science teachers improve their knowledge of science subject matter, this for the academic year beginning in September, 1958. It is anticipated that some 800 high school science and mathematics teachers will be enrolled with grants of $3000 each to approximately 50 teachers at each institute. Additional allowances for dependents and travel will be provided. Applications should be sent to the directors of the 17 institutes. Applications should be addressed to the directors of the institutes at: University of Chicago, University of Colorado, University of Illinois, Iowa State Teachers College, University of Michigan, University of North Carolina, Ohio State University, Oklahoma State University, Oregon State College, University of Pennsylvania, University of South Dakota, Syracuse University, University of Texas, University of Utah, University of Virginia,

Washington University (St. Louis), and University of Wisconsin.

RESEARCH FELLOWSHIPS AND ASSISTANTSHIPS IN METEOROLOGY AND OCEANOGRAPHY AT NEW YORK UNIVERSITY—Two fellowships are offered in the Department of Meteorology and Oceanography at New York University, one carrying a stipend of $2500 plus full tuition and fees for nine months, and the second carrying full suition and fees for nine months. In addition, a number of assistantships with an hourly rate of compensation are available. Inquiries should be addressed to the Assistant Dean in Charge of the Graduate Division, College of Engineering, New York University, University Heights, New York 53, New York. Applications must be filed by April 1, 1958.

POSTDOCTORAL RESIDENT RESEARCH ASSOCIATESHIPS AT NATIONAL BUREAU OF STANDARDS—These associateships are for the National Bureau of Standards in Washington, D. C., and Boulder, Colorado, or for the Naval Research Laboratory in Washington, D. C. The fields covered include various aspects bearing on geophysics. The associate will devote his efforts entirely to advanced training and research, and he may not receive aid from any other appointment, fellowship, or scholarship. The stipend is $7035 per year subject to income tax. Applications must be filed with the Fellowship Office, National Academy of Sciences, 2101 Constitution Ave., N. W., Washington 25, D. C., before January 13, 1958.

POSTDOCTORAL RESIDENT RESEARCH ASSOCIATESHIPS—These are available only at Argonne National Laboratory and Oak Ridge National Laboratory, where the necessary facilities and equipment for the approved program are available. The fields covered include various aspects bearing on geophysics. These associates will devote their entire effort to research and may not receive aid from any other appointment or grant. The stipend is $7035 per year subject to income tax. Applications must be on file with the Office of Scientific Personnel, National Academy of Sciences, 2101 Constitution Ave., N. W., Washington 25, D. C., not later than January 13, 1958.

GROUND-BREAKING CEREMONIES FOR NATIONAL RADIO ASTRONOMY OBSERVATORY—Ground-breaking ceremonies for this Observatory were held at Green Bank, West Virginia, October 17, this being the initial step in the effort on the part of the United States to get caught up with Great Britain, The Netherlands, Australia, and the Soviet Union in the development of radio astronomy. By July, 1958, an 85-ft steerable radio telescope will be in operation, and by 1960 a 140-ft instrument will be completed. These are still small compared with the 250-ft radio telescope in England and the 350-ft radio telescope in the USSR. The largest radio telescope in the United States at present is the 60-ft paraboloid telescope at Harvard. The Observatory will be under the direction of Associated Universities, Inc., supported by the National Science Foundation. Radio waves of extra-terrestrial origin were first detected by Karl G. Jansky in this country in 1932.

IMPORTANCE OF CONTINUITY IN RESEARCH ENDEAVOR—The Council of the American Meteorological Society recently sent a telegram to President Eisenhower and others in important positions in the government, pointing out the catastrophic effects on the advancement of science resulting from the current method of the Department of Defense. While the telegram related especially to meteorology, it underlines a difficult situation relating to all aspects of government-supported research, especially in the Department of Defense, which has been plagued by a turning off and on of funds which has led to great instability in the whole field of research and has had an adverse effect upon morale of cost-reimbursement, university-type contracts. There is great need for a research project and research endeavor in general to be on a much more dependable and stable basis than has frequently been the case in the past.

DOWNWIND EXPEDITION OF SCRIPPS INSTITUTION OF OCEANOGRAPHY—A cruise is now under way in the research vessels *Horizon* and *Spencer F. Baird* to the southeast Pacific, scientifically one of the least well-known ocean areas of the world. This is part of the IGY study of the great question, how do deep waters of the ocean move. The cruise will touch port briefly in Tahiti, Pitcairn Island, Juan Fernandez Island, Easter Island, and certain South American ports, and will cover some 38,000 to 40,000 miles. Not only will deep currents be measured by several methods, but heat flow measurements, ocean floor profiles, and samples for radiocarbon analysis will be taken.

STUDY OF CARIACO TRENCH—The research vessel *Atlantis* is now engaged in the study of the Cariaco Trench, a 4680-ft basin located near the coast of Venezuela that is shut off from the sea by a sill that permits no ocean water to enter from depths greater than 500 ft. The trench contains stagnant water with no free oxygen present, similar to conditions that exist in the Black Sea and some fjords but which have never been encountered before in the open sea. Long cores will be obtained from the bottom of the trench, and analyses and chemical studies will be made of the ocean water. The cruise is supported by funds from the Office of Naval Research.

NEW WORK ON INTERNATIONAL CRITICAL TABLES OF NUMERICAL DATA—An Office of Critical Tables has been established in the Division of Chemistry and Chemical Technology of the National Academy of Sciences-National Research Council, under the direction of Guy Waddington, to bring up to date the International Critical Tables of Numerical Data, 1926–1933. Since the publication of these tables there has been a profound increase in the amount of numerical data that will be of great value to research. The objectives of the Office of Critical Tables have been defined as follows: (1) to survey the needs for critical tables of numerical data; (2) to stimulate and coordinate preparation or compilation of critical tables on a continuing basis; (3) to develop uniform editorial standards for presentation of data so that the various tables projects will be uniform as to quality and usefulness; and (4) to provide a

central indexing and directory service with respect to all of the tables projects in progress.

METEOROLOGICAL RESEARCH REVIEWS—Volume 3 of *Meteorological Monographs*, numbers 12–20, has just been published by the American Meteorological Society, including articles dealing with weather observations, analysis and forecasting, radiometeorology, and atmospheric electricity. The authors are H. E. Landsberg, J. C. Bellamy, J. S. Marshall, W. E. Gordon, S. Petterssen, T. F. Malone, E. O. Hulburt, H. J. aufm Kampe, and H. K. Weickmann, with Alfred K. Blackadar serving as editor. It summarizes progress in meteorology in the fields covered from 1951 to 1955. Inquiries whould be sent to the American Meteorological Society, 3 Joy Street, Boston 8, Massachusetts.

SCIENTISTS NEEDED FOR OZONE MEASUREMENT WORK—The U. S. Weather Bureau is in search of a scientist for work on its ozone measurement program. The work involves the standardization of Dobson ozone spectrophotometers, and the candidate should have a strong background in optics and electronics. The person selected will spend about six weeks in Oxford, England, in training, following which he will visit ozone measuring stations in the United States, Canada, Alaska, and possibly Hawaii, examining the ozone spectrophotometers, making repairs as needed, and calibrating the instruments to be sure they are on the Oxford scale. The position is a Civil Service grade GS-9, $6250 per annum, with a maximum of GS-11, $7465 per annum. Travel expenses and per diem are in addition. Interested persons should address the Chief, U. S. Weather Bureau, Washington 25, D. C.

REPORT ON EVAPORATION AND EVAPOTRANSPIRATION RESEARCH—This report, relating to the United States and other countries, has been compiled by John R. Davis of Purdue University and summarizes the work in this field through the summer of 1956. The 87-page processed report contains information on active projects in every state and relating to 12 foreign countries, covering a total of 226 projects. Information concerning this publication may be secured from Agricultural Engineering, 420 Main Street, St. Joseph, Michigan.

IGY DATA RELATING TO METEOROLOGY—The World Meteorological Organization has issued a report describing the program for reproduction and distribution of meteorological publications taken during the International Geophysical Year. The information is to be reproduced on microcards, of which it is estimated that it will require about 18,500, with the anticipated cost per set in the neighborhood of $6000. Inquiries and orders whould be sent to the World Meteorological Organization, IGY Meteorological Data Centre, 1 Avenue de la Paix, Geneva, Switzerland.

NEW JOURNAL OF AMERICAN INSTITUTE OF PHYSICS—A new journal entitled *The Physics of Fluids* is to be issued by the American Institute of Physics, beginning in January, 1958. The editor is to be F. N. Frenkiel of the Applied Physics Laboratory, Johns Hopkins University, Silver Spring, Maryland. Subscription information may be obtained from the American Institute of Physics, 335 East 45th Street, New York 17, New York.

NEW GEOPHYSICAL OBSERVATORY IN MONTREAL—The Jesuits of Canada have recently established a Geophysical Observatory at the College Jean-de-Brebeuf in Montreal. The Observatory has one section relating to radiometeorology, under the direction of Ernest Gherzi, formerly of the Zi-Ka-Wei Observatory near Shanghai and the Macau Observatory, and a second section of seismology, under the direction of Maurice Buist. This is equipped with a complete set of Benioff seismographs. The Observatory has begun the issuance of a *Bulletin de Geophysique*, nos. 1 and 2 of which bear the dates March and September, 1957, respectively.

ANNUAL MEETING OF AMERICAN CONGRESS ON SURVEYING AND MAPPING AND AMERICAN SOCIETY OF PHOTOGRAMMETRY—This joint meeting will be held in Washington, March 23–29, 1958, at the Shoreham Hotel. For further information write to ACSM-ASP, 1515 Massachusetts Avenue, N.W., Washington 5, D. C.

SYMPOSIUM ON SALT WATER CONVERSION—A three-day Symposium on Salt Water Conversion was recently held in Washington under the sponsorship of the National Academy of Sciences-National Research Council, under arrangements with the Office of Saline Water of the Department of the Interior.

INVENTIONS WANTED—The Office of Technical Services and the National Inventors Council have put out a 30-page pamphlet relating to inventions wanted by the Armed Forces. Copies of this may be secured from, and inquiries should be addressed to the National Inventors Council, U. S. Department of Commerce, Washington 25, D. C.

PUBLICATION OF WORLD WEATHER RECORDS—Work toward preparation of the 1941–1950 volume of *World Weather Records* is proceeding on schedule at the U. S. Weather Bureau in Washington. More than 80 countries have cooperated by supplying the necessary data. The homogeneity of the records with those published in previous volumes has been studied by the staff of the Blue Hill Observatory of Harvard University. Funds for printing the volume have been supplied by the National Science Foundation. Publication is scheduled for 1958.

NATIONAL SCIENCE FOUNDATION REPORT ON SCIENTIFIC MANPOWER IN THE FEDERAL GOVERNMENT—A recent survey shows that 142,000 persons of a total of about two million Federal employees in 1953–1954 were engaged in research and development. About 37,000 were scientists and engineers, and the remainder were supporting personnel. In addition, another 65,000 scientists and engineers were employed in construction and operations work. Among the military personnel, about 77,000 were engaged in scientific and development ac-

tivities, of which about 9000 were scientists and engineers.

NEW SUBSIDIARY OF TEXAS INSTRUMENTS INCORPORATED—This company has established Texas Instruments, Limited, and has opened a new plant in Bedford, England, to manufacture transistors and other semiconductor devices. It is the first manufacturing plant of Texas Instruments to be established outside of the United States.

Personalia

HUGO BENIOFF, Professor of Seismology at the California Institute of Technology and President of the Section of Seismology of AGU, has recently been named as the recipient of the Arthur L. Day Medal by the Geological Society of America.

V. L. S. BHIMASANKARAM, Lecturer in Geophysics at Andhra University, Waltair, India, is pursuing his studies at the Geophysikalisches Institut in Göttingen under J. Bartels.

ARTHUR J. BOUCOT, formerly with the U. S. Geological Survey, who devoted last year to study in Europe under a Guggenmeim fellowship, has taken up new duties at the Massachusetts Institute of Technology as Assistant Professor of Geology.

JOHN C. CROWELL hzs been appointed Chairman of the Department of Geology at the University of California in Los Angeles under the rotating departmental chairmanship plan.

GERALD FITZGERALD, Chief Topographic Engineer of the U. S. Geological Survey since 1947, has recently retired. He originally joined the Survey in 1917 and served continuously, except for brief intermissions and special work during World War II, up to the time of his retirement.

PAUL D. FOOTE, retired Vice President of Gulf Oil Corporation in charge of research and development, has been given an interim appointment by President Eisenhower to be Assistant Secretary of Defense for Research and Engineering.

RICHARD P. GOLDTHWAIT, Professor of Geology at Ohio State University, has been on leave during the current year to study glaciers and glacial deposits in New Zealand under a Fulbright Grant. He also has made a trip to the Antarctic to inspect the glaciological work. He expects to return to his duties at Ohio State University about the middle of February, 1958.

HERBERT E. HAWKES has left his work at the Massachusetts Institute of Technology to accept a professorship in the Division of Mineral Exploration at the University of California in Berkeley.

J. BRACKETT HERSEY, Physical Oceanographer at Woods Hole Oceanographic Institution, has been appointed Associate Professor of Oceanography at the Massachusetts Institute of Technology, continuing his work at Woods Hole.

LEWIS D. KAPLAN has returned from a year of work at the Imperial College of Science and Technology in London and has taken up duties in the Department of Meteorology at the Massachusetts Institute of Technology.

PAUL F. KERR, Professor of Geology of Columbia University, has been named the recipient of the third K. C. Li Medal for meritorious achievement in advancing the science of tungsten.

RALPH W. POWELL has retired as Professor of the Department of Engineering Mechanics at Ohio State University and has taken up duties as Visiting Professor in the Department of Applied Mechanics at the University of Kansas.

E. P. ROTHROCK, formerly Professor of Geology and Head of the Department of Geology at the University of South Dakota, has resigned to enter upon private practice.

ROBERT E. STEVENSON has been named Professor and Chairman of the Department of Geology at the University of South Dakota.

JAMES S. SWEET has returned from a tour of duty as Consulting Hydrologic Engineer to the Colombian Government at Bogota and has resumed his duties at the U. S. Weather Bureau in Washington.

THOMAS F. THOMPSON, Project Manager in India for the Ralph M. Parsons Company, has completed his work in India and has returned to the United States. He is opening a consulting engineering geology office in San Carlos, California.

VICTOR VACQUIER, formerly Professor of Geophysics at the New Mexico Institute of Mining and Technology, has taken up duties as Research Geophysicist with the Scripps Institution of Oceanography.

WILLIAM S. VON ARX, Physical Oceanographer at Woods Hole Oceanographic Institution, has been appointed Associate Professor of Oceanography at the Massachusetts Institute of Technology, continuing his work at Woods Hole.

WALTER L. WHITEHEAD, who retired as Professor of Geology at the Massachusetts Institute of Technology in June 1957, continued as Director of the 1957 MIT Summer School of Geology at Crystal Cliffs, Nova Scotia, and is now serving as Lecturer in Geology at MIT and Visiting Professor at St. Francis Xavier University at Antigonish, Nova Scotia.

GEORGE D. WHITMORE has been named Chief Topographic Engineer of the U. S. Geological Survey. He had served as Deputy Chief since 1947.

HANS F. WINTERKORN, Professor of Civil Engineering at Princeton University, has been given the Cross of Merit of the Federal Republic of Germany.

LADISLAO ADLER, retired geophysicist of the Shell Oil Company, died September 4, 1956, at the age of 59. He was born in Hungary, but after the war became a stateless citizen living in Canada. He completed his formal studies at the Royal Technical University of Budapest as a civil engineer and entered upon work relative to the determination of gravity and in geophysical exploration which he continued until the time of his retirement in 1951. He had been a member of AGU since 1951.

RICHARD C. HUBLEY, glaciologist active in the IGY work on glaciers in Alaska, died October 28, 1957, from exposure on the McCall Glacier in Alaska. He was born in Tacoma, Washington, in 1926, took his Bachelor of Science degree from the University of Washington in 1950, and his Master of Science degree from the same University in 1952. He had been a member of AGU since 1952.

E. RAYMOND SHEPARD, retired geophysicist, died October 17, 1957, at the age of 77. He was born in Salt Lake City but spent most of his boyhood in Oregon. He took his baccalaureate degree from the University of California in 1904 and his master's degree from Harvard University in 1906. In 1914 he entered the service of the Bureau of Standards and became an authority on underground corrosion and geophysics. In subsequent years he became a consulting engineer with headquarters in Chicago. He later took up duties with the Corps of Engineers, from which work he retired in 1950. He had been a member of AGU since 1934.

CARL STÖRMER (FREDRIK CARL MÜLERTZ STÖRMER), world renowned authority on the aurora, died August 13, 1957 at the age of 82. He was born September 3, 1874 at Skien, Norway, attended the University of Oslo and the University of Paris, and served as a *Privatdocent* at Göttingen in 1902. In 1903 he became Professor of Pure Mathematics at Oslo, which post he filled throughout his career. His great work in the field of the aurora and geomagnetism forms a large part of our present basic knowledge of these phenomena.

Informal Report on the Eleventh General Assembly of the International Union of Geodesy and Geophysics Held in Toronto, Canada, September 3-14, 1957

The Eleventh General Assembly of the International Union of Geodesy and Geophysics was held in the delightful and spacious atmosphere of the University of Toronto in the heart of Canada's second largest city from September 3 to 14, 1957. Maurice Ewing served as Chief Delegate from the United States. Principal delegates to the Associations were: Geodesy, Charles A. Whitten; Seismology and Physics of the Earth's Interior, Harry H. Hess; Meterorology, Helmut E. Landsberg; Geomagnetism and Aeronomy, Elliott B. Roberts; Oceanography, Roger R. Revelle; Volcanology, J. Frank Schairer; and Hydrology, Ray K. Linsley.

Registration began on September 1, but Committees and Commissions began their meetings on August 30. The opening plenary session, which drew the group together for the first time, was held on the morning of September 3 and was addressed by Prime Minister Diefenbaker of Canada, Speaker Downer of the Legislative Assembly of the Province of Ontario, and Mayor Phillips of the City of Toronto. President Ramanathan gave his presidential address presenting his thoughts on the progress and activities of geophysics, and General Secretary Laclavere gave a brief report for the triennium just closing.

Twelve hundred registered as scientists and technologists to take formal part in the scientific proceedings of the Union and its Associations. The total, including family members, was about 1400. Forty-four countries of the 52 members sent delegations as follows: Argentina, Austria, Australia, Belgium, Burma, Canada, Chile, Czechoslovakia, Denmark, Dominican Republic, Egypt, Finland, France, Germany, Great Britain, Greece, Holland, Hungary, India, Iran, Ireland, Israel, Italy, Japan, Mexico, New Zealand, Norway, Pakistan, Peru, Philippines, Portugal, Poland, Rhodesia and Nyasaland, Rumania, Spain, Sudan, Sweden, Switzerland, Tunisia, Turkey, U. S. S. R., United States, Viet-Nam, and Yugoslavia. In addition, five nonmember countries sent observers as follows: Republic of China, Cuba, Honduras, Nigeria and Venezuela.

The headquarters for the General Assembly was Hart House, a spacious gothic building providing ample facilities for registration, meals, distribution of mail, the trade exhibit of scientific books and instruments, and as a general gathering place. The offices of the officers of the Union were in near-by University College, a beautiful gothic structure that dates back more than 100 years. All of the sessions of the Associations were held in University buildings within about a half-mile radius of Hart House. Many of the participants lived in the college dormitories.

All seven Associations had very full meetings and, in addition to several joint symposia between and among Associations, some Associations had two or three meetings in progress at the same time. Thus it was not possible for a person to hear all of the papers in which he had interest. The outstanding papers were many, but outstanding among the symposia was a joint one held by Meteorology, Oceanography, and Hydrology on the water balance of the Earth. This resulted in the appointment of a Joint Committee on Evapotranspiration. Other important symposia related to aeronomy; magnitude of earthquakes and earthquake energy; crustal structure of continents and ocean basins; atmospheric diffusion and convection; numerical and graphical methods of dynamical weather prediction; problems of upper atmosphere; and atmospheric chemistry.

The Association of Volcanology modified its organization to reflect broader interests. Four Sections were established as follows: Active Volcanoes, Volcanophysics, Physical Chemistry of Magmas, and Paleovolcanology.

Several of the Associations plan to hold symposia in the interval prior to the next General Assembly, including Geodesy, Meteorology, Geomagnetism and Aeronomy, and Hydrology. The theme of two projected symposia in Hydrology are snow and ice, planned to be held in Austria in 1958, and forest and waters, planned to be held in Germany in 1959. Three planned in Meteorology are on ozone, atmospheric radiation, and atmospheric diffusion and air pollution.

The results of the Union and Association elections and Committee designations were as follows:

Union—President, J. Tuzo Wilson (Canada); Vice Presidents, V. Beloussov (U. S. S. R.) and W. A. Heiskanen (Finland); General Secretary, G. Laclavere; members of Bureau at Large, G. E. R. Deacon (Great Britain), J. W. Joyce (U. S. A.), and C. Tsuboi (Japan); members of the Finance Committee, K. Hilding Beij (U. S. A.), M. Goldschmidt (Israel), J. M. Rayner (Australia), A. Romana (Spain), and J. Vignal (France).

Geodesy—Honorary Presidents, F. A. Vening Meinesz (The Netherlands), C. F. Baeschlin (Switzerland), W. D. Lambert (U.S.A.), and J. de Graaff-Hunter (Great Britain); President, C. Cassinis (Italy); Vice Presidents, C. A. Whitten (U.S.A.), and T. J. Kukkamäki (Finland); Secretary and Director of Central Bureau, P. Tardi (France); Assistant Secretaries, J.-J. Levallois (France) and F. L. Culley (U.S.A.). *Section of Triangulation*—President, A. Marussi (Italy); Secretary, L. Asplund (Sweden). *Section of Leveling*—President, T. J. Kukkamäki (Finland); Secretary, L. Cahierre (France). *Section of Geodetic Astronomy*—President, R. Roelofs (The Netherlands); Secretary, P. J. L. Melchior (Belgium). *Section of Gravity*—President, B. C. Browne (Great Britain); Secretaries, Donald A. Rice (U.S.A.) and Suzanne Coron (France). *Section of Geoid*—President, W. A. Heiskanen (Finland); Secretaries, I. D. Zhongalovitch (U. S. S. R.) and K. Ledersteger (Austria). *Permanent Commission European Triangulation*—President, M. Kneissl (Germany). *Permanent Commission European Leveling*—President, O. Simonsen (Denmark). *Permanent Commission S.E. Asia Tri-*

(Left to right from top) (1) Girard Tison (Belgium); J. J. Levalois (France), Assistant Secretary, Association of Geodesy; A. A. J. Massart (Belgium); R. A. Verlaine (Belgium); J. Rothé (France), Secretary, Association of Seismology and Physics of the Earth's Interior; J. L. Koenigsfeld (Belgium); L. J. Tison (Belgium), Secretary, Association of Hydrology (2) J. Th. Thijsse (The Netherlands), retiring President, Association of Hydrology; K. H. Beij (U. S. A.), Member, Finance Committee, IUGG (3) W. A. Heiskanen (Finland), new Vice President, IUGG (4) G. Laclavere (France), General Secretary, IUGG; K. R. Ramanathan (India), retiring President, IUGG; J. Tuzo Wilson (Canada), new President, IUGG (5) V. Beloussov (U.S.S.R.), new Vice President, IUGG; J. Tuzo Wilson (6) C. Morelli (Italy); J. A. Peoples, Jr. (U. S. A.); J. L. Worzel (U. S. A.) (7) R. Stoneley (U.K.); K. E. Bullen (Australia), retiring President, Association of Seismology and Physics of the Earth's Interior; Sir Harold Jeffreys (U. K.), new President, Association of Seismology and Physics of the Earth's Interior (8) L. B Slichter (U. S. A.); L. V. Berkner (U. S. A.).

angulation—President, G. Bomford (Great Britain). *Gravimetric Commission*—President, P. Lejay (France). *General Reporters*—Triangulation, C. Trombetti (Italy); Leveling, A. Waalewijn (The Netherlands); Geodetic Astronomy, H. S. Helstrup (Norway); Gravity, G. Boaga (Italy); Geoid, G. Bomford (Great Britain) and W. A. Heiskanen (Finland). *Special Reporters*—Earth Tides, P. J. L. Melchoir (Belgium); Radio-Electric Methods, C. A. Hart (Nigeria).

Seismology and Physics of the Earth's Interior—President, Harold Jeffreys (Great Britain); Vice Presidents, J. Hodgson (Canada) and Y. V. Richnichenko (U.S.S.R.); Secretary General, J. Rothé (France); Executive Committee: H. Pekeris (Israel), Anne R. Ritsema (Indonesia), Inge Lehmann (Denmark), E. Vesanen (Finland), and K. E. Bullen (Australia). *Committee for the International Seismological Summary*—Chairman, R. Stoneley (Great Britain); members, Harold Jeffreys (Great Britain), Leonard M. Murphy (U.S.A.), K. E. Bullen (Australia), and N. Kondorskaya (U.S.S.R.). *Commission on the Physics of the Earth's Interior*—Tectonophysics, V. Beloussov (U.S.S.R.) and F. A. Vening Meinesz (The Netherlands); Geochronology and Radioactivity, J. Tuzo Wilson (Canada) Geothermy, Edward Bullard (Great Britain); Elasticity and Plasticity, Harold Jeffreys (Great Britain) and R. Stoneley (Great Britain); Gravimetric Interpolation, J. Goguel (France). *Commission for the Study of European Seismological Problems*—President, W. Hiller (Germany); Secretary, P. Caloi (Italy); members, M. Båth (Sweden), J. Bonelli Rubio (Spain), M. J. Debrach (Morocco), H. A. Ferreira (Portugal), A. Galanopoulos (Greece), G. Grenet - (Algeria), R. Ingram (Ireland), A. Kvale (Norway), I. Lehmann (Denmark), J. Mihailovic (Yugoslavia), E. Peterschmitt (France), Nuriye Pinar (Turkey), J. C. Scholte (The Netherlands), E. Tillotson (Great Britain), M. Toperczer (Austria), E. Tryggvason (Iceland), J. M. Van Gils (Belgium), and E. Vesanen (Finland).

Meteorology—President, Jacques Van Mieghem (Belgium); Vice Presidents, Horace R. Byers (U.S.A.) and A. M. Oboukhov (U.S.S.R.); Secretary, Reginald C. Sutcliffe (Great Britain). *Commission for Radiation*—President, F. Möller (Germany); Vice President, W. Mörikofer (Switzerland); Secretary, G. D. Robinson (Great Britain); U. S. members, S. Fritz and Z. Sekera. *Commission for Atmospheric Ozone*—President, G. M. B. Dobson (Great Britain); Secretary, Charles Normand (Great Britain); U. S. members, Max A. Kohler, Harry Wexler, A. Adel, and Richard Craig. *Commission on Atmospheric Radioactivity and Chemistry*—U.S. members, Lester Machta and C. E. Junge. *Joint Commission (with IAGA) on Upper Atmosphere*—(see IAGA, below). *Joint Commission (with IAGA) on Atmospheric Electricity*—(see IAGA, below). *Joint Commission (with IAPO and IASH) on Precipitation*—(see IASH below); U. S. members, G. S. Benton and R. K. Linsley. *Joint Commission (with IAGA) on Solar and Terrestrial Relationships*—U. S. Reporter, O. R. Wulf. *Joint Commission (with IASH) on Evapotranspiration*—U. S. member, Max A. Kohler.

Geomagnetism and Aeronomy—President, J. Kaplan (U.S.A.); Vice Presidents, A. G. Kalashnikov (U.S.S.R.) and V. Laursen (Denmark); Secretary and Director of the Central Bureau, J. O. Cardus (Spain); Executive Committee, J. Bartels (Germany), T. Nagata (Japan), M. Nicolet (Belgium), J. M. Rayner (Australia), O. Schneider (Argentina), and E. Thellier (France). *Committee 1 (Observatories)*—Chairman, E. B. Roberts (U.S.A.); U. S. members, H. F. Johnston and J. H. Nelson. *Committee 2 (Aurora and Airglow)*—Chairman, C. T. Elvey (U.S.A.); U. S. members, C. W. Gartlein, A. B. Meinel, and F. E. Roach. *Committee 3 (Aeronomy)*—Chairman, M. Nicolet (Belgium); U. S. members, J. W. Townsend, Jr., C. T. Elvey, H. Friedman, E. O. Hulburt, H. E. Newell, F. E. Roach, and J. A. Simpson. *Committee 4 (Secular Variation and Paleomagnetism)*—Chairman, T. Nagata (Japan); U. S. members, J. R. Balsley and E. H. Vestine. *Committee 5 (World Magnetic Survey and Magnetic Charts)*—Honorary Chairman, J. Keranen (Finland); Chairman, E. H. Vestine (U.S.A.); U. S. member, E. B. Roberts. *Committee 6 (Lunar Variations)*—Chairman, S. Chapman (Great Britain). *Committee 7 (Comparisons of Magnetic Standards)*—Chairman, V. Laursen (Denmark); U. S member, E. B. Roberts. *Committee 8 (Magnetic Instruments)*—Chairman, J. H. Nelson (U.S.A.); U. S. members, L. R. Alldredge, P. St. Amand, and V. Vacquier. *Committee 9 (Characterization of Magnetic Activity)*—Chairman, J. Bartels (Germany); U. S. member, H. F. Johnston. *Committee 10 (Rapid Variations and Earth Currents)*—Chairman, A. Romana (Spain); U. S. member, J. H. Nelson. *Committee 11 (History of Geomagnetism and Aeronomy)*—Chairman, N. Pushkov (U.S.S.R.); U. S. member, E. B. Roberts. *Joint Committee (with IAM) on Atmospheric Electricity*—Honorary Chairman, H. Norinder (Sweden); Chairman, L. Koenigsfeld (Belgium); U. S. members, H. R. Byers and Ross Gunn. *Joint Committee (with IAM) on Upper Atmosphere*—Chairman, M. Nicolet (Belgium); U. S. members, J. Kaplan, W. W. Kellogg, H. N. Newell. *Joint Commission on Ionosphere*—Members, S. Chapman (Great Britain), K. Maeda (Japan), D. R. Bates (Ireland), and M. Nicolet (Belgium). *Joint Commission (with IAM) on Solar and Terrestrial Relationships*—U.S. member, E. H. Vestine. *Assistant Editor for the Toronto Transactions*—T. R. Kaiser (Great Britain).

Oceanography—President, H. Mosby (Norway); Vice Presidents, J. N. Carruthers (Great Britain) and V. Kort (U.S.S.R.); Secretary, E. B. Kullenberg (Sweden); Deputy Secretary, M. Marc Eyries (France); Executive Committee, Pier Groen (The Netherlands), G. Böhnecke (Germany), H. B. Hachey (Canada), K. Kidaka (Japan). *Committee on Tides*—Chairman, J. Proudman (Great Britain); Secretary, A. Gougenheim (France); U. S. member, L. P. Disney. *Committee on Mean Sea Level*—Chairman, A. T. Doodson (Great Britain); Secretary, J. R. Rossiter (Great Britain); U. S. members, L. P. Disney and J. Pattullo. *Committee on Oceanographical Observations from Weather Ships*—Chairman, D. C. Archibald (Canada); Secretary, O. H. Saelen (Norway); U. S. members, John Lyman, R. B. Montgomery, K. M. Rae. *Committee on Bibliographical Classification*—Chairman, F. Model (Germany). *Committee on the International Geophysical Year*—Chairman, C. A. D'Iselin (U.S.A.); Secretary, G. E. R. Deacon (Great Britain); Correspondent with CSAGI, G. M. Laclavere (France), U. S. member, R. Revelle. *Committee on Current Measurements*—Chair-

man (Editor), H. Weidmann (Germany); U. S. member, W. S. Von Arx. *Committee on the General Bathymetric Chart of the Oceans*—Chairman, G. Böhnecke (Germany); U. S. members, B. C. Heezen and H. W. Menard. *Committee on Chemical Oceanography*—Chairman, L. H. N. Cooper (Great Britain); Secretary, D. E. Carritt (U.S.A.). *Joint Committee (with IASH and IAM) on Evapotranspiration*—(see IAM, above, and IASH, below); Members, H. Mosby (Norway) and H. Charnock (Great Britain). *Special Committee on Oceanic Research*—IAPO and UGGI members, H. Mosby (Norway), G. Böhencke (Germany), G. E. R. Deacon (Great Britain), and M. N. Hill (Great Britain). *Standard Sea Water Service, 1957–1960*—In charge, H. Thomsen (Denmark).

Volcanology—President, Alfredo Rittman (Switzerland); Vice President, J. F. Schairer (U.S.A.); Secretary, F. Signore (Italy). *Section of Active Volcanoes*—Chairman, M. Neumann van Padang (Netherlands). *Section of Volcanophysics*—Chairman, V. R. Gorshkov (U.S.S.R.). *Section of Physical Chemistry of Magmas*—Chairman, H. Kuno (Japan). *Section of Paleovolcanology*—Chairman, B. Geze (France).

Hydrology—Honorary Presidents, J. T. Thijsse (The Netherlands), G. De Marchi (Italy), and Jan Smetana (Czechoslovakia); President, H. G. Wilm (U.S.A.); Vice Presidents, W. Allard, (Great Britain), Dino Tonini (Italy), and Wilhelm Friedrich (Germany); Secretary, L. J. Tison (Belgium). *Commission on Ground Waters*—Honorary President, A. Nelson Sayre (U.S.A.); President, W. J. F. M. Krul (The Netherlands); Vice Presidents, G. V. Bogomolov (U.S.S.R.) and G. B. Maxey (U.S.A.); Secretary, S. Buchan (Great Britain); U. S. Correspondent, G. B. Maxey. *Commission on Snow and Ice*—President, Richard Finsterwalder (Germany); Honorary Vice Presidents, J. E. Church (U.S.A.) and P. L. Mercanton (Switzerland); Vice Presidents, Albert Bauer (France) and U. Nakaya (Japan); Secretary, Patrick D. Baird (Great Britain); U. S. Correspondent, C. C. Warnick. *Commission on Land Erosion*—President, J. Tixeront (Tunis); Vice Presidents, H. Kuron (Germany) and Yousef M. Semaika (Egypt); Secretary, Thomas Maddock, Jr. (U.S.A.); U. S. Correspondent, L. B. Leopold. *Commission on Surface Water*—President, Louis Serra (France); Vice Presidents, A. Volker (The Netherlands) and J. Lambor (Poland); Secretary, Peter Kasser (Switzerland); U. S. Correspondent, A. J. Cooper. *Commission on Instruments*—Chairman, J. B. Schijf (The Netherlands). *Joint Commission (with IAM) on Precipitation*—Chairman, Louis Serra (France). *Joint Commission (with IAM and IAPO) on Evapotranspiration*—U. S. member, G. Earl Harbeck. *Steering Committee, Evaluation of Dissolved Salts*—Members, G. A. Avsuk (U.S.S.R.), W. H. Durum (U.S.A.), L. J. Tison (Belgium), G. C. Chaterji (India), and C. R. Vilela (Argentina).

A number of resolutions were passed which will be published in full by the International Union in due course. One involved the establishment of a standard for the velocity of light and electromagnetic waves as 299,792.5 ± 0.4 km per second in vacuum. Another related to the encouragement of the universal use of alternating current rather than direct current for railways because of the effect of direct current on magnetic observations. Another resolution related to the drilling of a deep hole at some point in the Pacific where the Earth's crust is thin in an effort to penetrate through the crust of the Earth across the Mohorovicic dicontinuity into the mantle of the Earth.

Not at all neglected were the social aspects of this gathering which gave opportunity for the delegates to meet informally under friendly circumstances. Included were an opening reception in the Royal Ontario Museum, excursions to Niagara Falls and to the lake region north of Toronto, including Georgian Bay, an evening concert by the symphony orchestra of the Canadian Broadcasting Company at which Glen Gould appeared as piano soloist, and a soiree on the evening before the closing day of the Assembly.

A final plenary session was held on September 14 at which the Union elections were ratified and the officers installed. This final plenary session included a report by the retiring President, a report of the General Secretary providing for ratification of the action of the Council relating to the resolutions, changes of the Statutes and By-Laws, the election of Union officers, and the selection of the meeting place for 1960. The Associations also reported briefly, announcing officers and committees elected, and resolutions adopted. Closing farewell addresses and resolutions of thanks were also presented. Finland was selected as the site for the Twelfth General Assembly with the dates of July 25 to August 8, 1960.

Following the closing of the Assembly, a three-day field trip was made by some of the delegates to Sudbury, Ontario, stopping at Parry Sound on the outgoing trip and at Ottawa on the return trip.

WALDO E. SMITH

Union, Section, and Committee Activities

COMMITTEE APPOINTMENTS—In the August 1957 issue of the *Transactions*, page 600, the committees of the current triennium are outlined. The following information is given relative to additional appointments and changes and with respect to Section committees:

Changes in Standing Committees:

Editorial and Publication: Add Hugh Odishaw

Membership: Paul A. Smith (on membership admissions) replaces W. E. Hiatt; add Nelson C. Steenland (on industrial and commercial memberships)

Changes in Special Committees:

Geophysical and Geological Study of Continents; Add J. C. Harrison, Charles B. Officer, Jr., James A. Peoples, Jr., and Frank Press

Advisory Editorial Board on Russian Translations (new Committee): Perry Byerly (Chairman), Walter B. Langbein, John Lyman, F. W. Reichelderfer, A. E. Scheidegger, Waldo E. Smith, Victor Vacquier

Advertising: Add Samuel C. Coroniti

Geophysical Education (new Committee): John E. Nafe (Chairman), H. R. Byers, C. T. Elvey, H. H. Hess, Patrick M. Hurley, Frank Press, Roger Revelle, Athelstan Spilhaus, C. W. Thornthwaite, James A. Van Allen, H. G. Wilm

Changes in Regional Committees:

Mid-Pacific Region (Geophysical Society of Hawaii) (new officers): Thomas S. Austin (President), Robert B. Campbell (Vice President), Saul Price (Secretary-Treasurer), James F. McGary, Colin Ramage

Changes in Representatives of AGU:

American Geological Institute: Board of Governors—Delete Henry R. Joesting; add James R. Balsley and Walter H. Bucher

U. S. National Committee for the International Geophysical Year: Maurice Ewing replaces N. C. Gerson

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Executive Committee—Harry H. Hess (President), Patrick M. Hurley (Vice President), Benjamin F. Howell, Jr. (Secretary), Francis Birch (Past President)

Special Announcements

PACIFIC SOUTHWEST REGIONAL MEETING IN PASADENA, FEBRUARY 6–7, 1958—Plans for this meeting are now well along. Interested persons should get into touch with the Chairman of the Regional Committee, Vito A. Vanoni (California Institute of Technology, Pasadena, Calif.), or with Eugene N. Bollay (North American Instruments, Inc., 2420 N. Lake Ave., Altadena, Calif.), Chairman of the Program Committee.

THIRTY-NINTH ANNUAL MEETING TO BE HELD IN WASHINGTON, D. C. MAY 5–7, 1958—Your attention is invited to the extended announcement concerning this meeting on pages 797–798 of the October issue of the *Transactions*. Note that titles and abstracts of papers for the programs should be sent in as soon as possible to the appropriate persons and that in general the closing date is March 5, 1958, except for Meteorology for which the closing date is January 20, 1958.

Abstracts must be informative and concise, and not more than 150 words (see Suggestions to Authors in the *Transactions* of April 1957, p. 285, for ideas regarding abstracts).

Standard-size slide projectors (3¼ x 4) will normally be available at the meeting, but other facilities will be provided only if specially requested well in advance. Persons inexperienced in the proper preparation of figures and tables for the making of slides should write to the AGU office requesting information on this. One general rule, however, is to avoid crowding and attempting to show too much on one slide. More than two or three curves on one slide tend to be confusing. Extra large sized lettering is essential.

In case the paper is being submitted for publication in the *Transactions*, complete manuscripts, double-spaced, in triplicate, with figures and tables should be in the AGU office by April 15, 1958.

The Section on Meteorology is to meet jointly with the American Meteorological Society. Jack C. Thompson (U. S. Weather Bureau, Washington 25, D. C.) is Chairman for the joint program and material relating to the program should be sent directly to him. The meeting in Meteorology may extend to include May 8. The program will emphasize meteorological exploration of the high atmosphere, and interactions between macro-, meso-, and micro-meteorological scales of weather phenomena. Other sessions will be devoted to the general circulation of the atmosphere, cloud physics, recent developments in forecasting theory and practice, and meteorological observations, as well as other topics for which sufficient papers are received. Contributions of the following types will be welcomed: (1) summaries of original research, (2) broad surveys of particular fields of research and development, and (3) descriptions of other meteorological activities which are of wide general interest.

Block bookings have been made at three hotels as follows:

Roger Smith Hotel, Pennsylvania Ave., at 18th St., N. W.
Willard Hotel, Pennsylvania Ave. at 14th St., N. W.
Raleigh Hotel, Pennsylvania Ave. at 12th St., N. W.

Make your room reservation early directly with the hotel of your choice, citing the AGU block booking if you write to one of the three hotels noted.

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NATIONAL ACADEMY OF SCIENCES

Number 5 • November 1957

IGY BULLETIN

A monthly survey by the U. S. National Committee for the International Geophysical Year. Established by and part of the National Academy of Sciences, the Committee is responsible for the U. S. International Geophysical Year program in which several hundred American scientists are participating and many public and private institutions are cooperating.

Preliminary Summary of USSR Satellite Reports

The material below is based upon a composite of unofficial reports as of October 26, 1957, on the first USSR satellite to be placed in orbit. The reports were gathered from press coverage of Radio Moscow, direct reports to the USNC-IGY, and public reports of various radio and visual tracking activities.

Launching: The official USSR announcement attributed to Radio Moscow on the evening of October 4, 1957, said that the USSR satellite was launched earlier that day at a speed of "about 8000 meters (26,000 ft) per second," at an angle of 65° to the equator and at a maximum height of 560 miles. Scientists in Washington, D. C., were reported to have estimated that the satellite was launched in a northeasterly direction from a point north of the Caspian Sea at approximately 5 pm EDT, October 4.

No details regarding the launching vehicle were made available. However, on October 7 the press quoted Y. A. Pobedonostsev as stating in *Soviet Aviation* that the three-stage carrier reached a speed of 4340–4650 mph before the first stage fell, 1–2 min after launching. Inclining from the vertical about a mile up, it reached an angle of 45° when the second stage fired, boosting the speed to 11,160–12,400 mph before falling. The rocket coasted up to a point about 625 mi from the launching site, where the third stage fired bringing the speed to 18,000 mph. The satellite was then released.

Pravda was quoted in the press as stating that an "extremely accurate and effective system of automatic controls was designed for the rocket. . . ." Pravda also reported that the carrier-rocket and its discarded nose cone were both accompanying the satellite in orbit.

Satellite Characteristics: Radio Moscow's first announcement stated that the USSR satellite is a polished sphere weighing 83.6 kg (over 183 lbs) and 58 cm in diameter (nearly 23 in). Later information released in Moscow revealed that the sphere's four antennae measure from 7 ft 10.5 in to 9 ft 6 in. The antennae were folded back, then sprung into position upon ejection. It was stated that the satellite's visibility was comparable to stars of the fourth to ninth magnitude.

A. A. Blagonravov, a USSR delegate to the recent CSAGI Conference on Rockets and Satellites in Washington, D. C., was quoted in the press as stating that the satellite contained nitrogen for cooling purposes.

Instrumentation: The first announcement by Radio Moscow indicated that there were two transmitters in the satellite, one operating at 20.005 mc and the other at 40.002 mc. The pulse of each signal was 0.3 sec, followed by a pause of similar length during which the other signal was transmitted. (On October 8, the signals were not received for several hours. Later, signals resumed but became continuous.) The announcement stated that "The power of the transmitter

is such as to insure reliable reception by a broad range of amateurs." It was later specified to be one watt. US monitors agreed that the signals were modulated with telemetry data.

Blagonravov informed the CSAGI Conference that temperatures were being reported by the satellite. Later, Pravda was reported to say that temperature and other data were being transmitted. Near the end of the satellite's first week in orbit, Prof. Valerian Krasovsky reportedly stated on Radio Moscow that the atmospheric temperature and density were both indicated to be much lower than had been previously thought. A report the following day added that the satellite "is now being bombarded by micrometeorites." (These were generally thought to consist of debris from the comet Giacobini-Zinner.) It is assumed that this statement was based upon data supplied by appropriate instrumentation in the satellite.

Observations: First US radio reception of the satellite's signals was reported by RCA Communications, Inc., at Riverhead, L.I. The observation occurred at 8:07 pm, EDT, October 4, the day of the launching. At 8:15, the signal was strongest from the south. First reception at the Naval Research Laboratory in Washington, D. C., was at 8:30 pm. (By October 6, six of ten Minitrack stations had been converted from 108 mc—the recommended frequency—to 20 and 40 mc, in order to facilitate radio tracking of the USSR satellite.)

Radio reception was soon general and reports of continuous monitoring were received from Antartic IGY stations, including the South Pole—which is in a position to hear the satellite on virtually every passage—as well as from IGY Drifting Station A, an ice floe about 500 miles from the North Pole.

Reports from the Amundsen-Scott South Pole Station indicated that the satellite's radio signals cut in abruptly but faded out gradually and that there were numerous variations in signal strength, duration, and pulse rate. These variations are believed to be at least partially caused by ionospheric and propagation path conditions, factors that will be studied with the help of tape recordings of the radio signals.

The USSR was reported in the press to be encouraging amateur assistance, offering special cards to hams reporting receipt of the satellite's radio signals.

Radio Moscow announced on October 26 that "the satellite's radio station, having used up its reserve of power," had stopped working. On the same day, the Naval Research Laboratory reported that no signals had been received by Minitrack stations since 5:50 pm EDT, October 25, and that no other information had been relayed to NRL from other radio receiver sources since 7:10 pm EDT, October 25.

Visual observations were more difficult since the satellite's times of passage in the western hemisphere did not, during its first week, coincide with dawn or dusk, when visual fixes might be possible. However, at 6:23 am, EDT, on October 10, James Plato, a member of a New Haven, Conn., Moonwatch Team, sighted the carrier-rocket, then about 600 miles in advance of the satellite. (Much larger, the rocket is easiest of the three orbiting objects to see.) A 5.5-power wide-field telescope was used to find the rocket in the north-west sky at approximately 40° above the horizon.

Press reports indicated that on October 9 all three orbiting objects were detected by a giant radar installation at the Stanford Research Institute at Palo Alto, Calif.

Photographs were reported made by October 11 at Ft. Churchill, Manitoba, in Alberta, and in Stockholm.

In the USSR, it was indicated, 30 telescopes were in use to track the satellite at Leningrad Pulkovo Observatory and a special station had been established at Petrodvorets.

Orbit: Radio Moscow's first announcement stated that the satellite had been placed in an elliptical orbit with an apogee of approximately 560 miles and at an angle in-

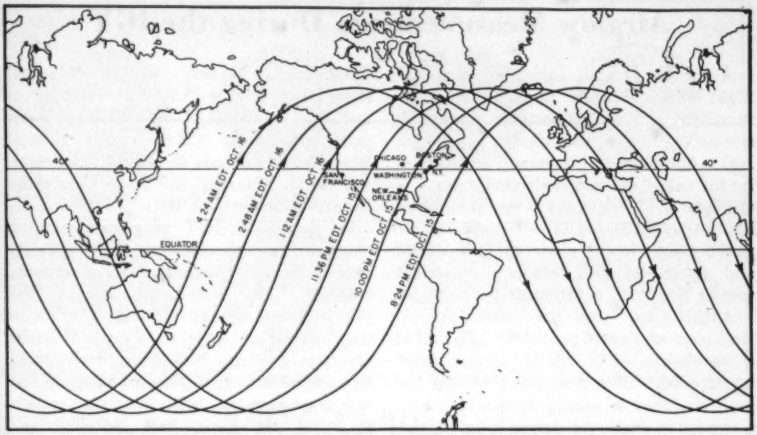

Fig. 1. *Example of Orbit Prediction of USSR Satellite Prepared by U. S. Naval Research Laboratory. (Times computed for 40°N; released October 15, 1957, 11:30 am.)*

clined about 65° to the equatorial plane. The period of rotation was at first described as 95 minutes. The following day, it was stated by Radio Moscow that, "According to precise calculations, the period of its circling the earth lasts 1 hour 36.2 minutes." On October 10, NRL reportedly fixed the orbital period at 96.1 minutes. On several occasions, NRL has described the mean height of the satellite as about 400 mi.

(The path of the USSR satellite has been predicted daily by NRL. The prediction for October 15 appears in Figure 1.)

The press reported that calculations made at Bonn University fixed the satellite's perigee at 156 miles, its apogee at 559 miles and the median height at 357 mi.

On October 9, Pravda was reported to have said of the satellite's orbit that its "altitude changes periodically, reaching a highest point of approximately 1000 km. At present the . . . perihelion is in the northern hemisphere and its apogee in the southern hemisphere."

Precise determinations of the carrier-rocket's orbit were announced by the Smithsonian Astrophysical Observatory on October 11. Apogee was described as 583 miles, perigee as 143 miles. Eccentricity of the orbit was fixed at .05. Precession amounted to a little more than 3° daily. Time for a complete circuit was set at 96.03 minutes. (The rocket was believed to be orbiting faster and generally lower than the satellite itself.) On October 26, Tass was quoted in the press as saying that as of that date the satellite took 95.31 minutes for each orbital period, compared with the original time of 96.2 minutes.

While Blagonravov informed the CSAGI Conference on October 5 that the satellite was designed to orbit for at least two weeks, Radio Moscow stated, on October 10, that "The minute diurnal variation in the [satellite's] time for revolution proves that the satellite will continue encircling the earth for a long time."

Airglow Measurements During the IGY

A faint, usually invisible glow—the night airglow—occurs in the earth's atmosphere, and is a subject of considerable scientific interest and study during the IGY. Although not generally identifiable by the naked eye, airglow supplies much of the light of the night sky. One investigator has roughly estimated its contribution to the visible light—in the absence of moonlight and aurora—at 40%, which is somewhat greater than that contributed by starlight.

Airglow was first discovered by astronomers who noted persistent radiation at a wavelength of 5577Å on long-exposure spectrograms. Since then, this green line has been identified as arising from a forbidden transition in which the oxygen atom emits a quantum of light of wavelength 5577Å while falling to a lower energy state.

Two red emission lines (at 6300Å and 6363Å) have also been discovered in the airglow, and are known to arise from the decay of oxygen atoms from the lower of the green line transition states. The other principal features of the night airglow are the yellow lines of sodium at 5890Å and 5896Å, and the complex system of molecular emissions (chiefly in the infrared) which arise from the hydroxyl radical (OH). These hydroxyl bands are intrinsically so strong that if they were concentrated in the visual region of the spectrum they would be as bright as a prominent aurora and would cause a permanent twilight. Their total intensity is approximately 5000 times that of the oxygen green line in the airglow.

France, Japan, the USSR, India, Australia, and the US are conducting airglow observational programs during the IGY. In addition, Mexico, Peru, and Argentina are collaborating in the American program. The United States stations are situated at Thule, Greenland; College, Alaska; Rapid City, South Dakota; Fritz Peak, Colorado; Sacramento Peak, New Mexico; and, on a cooperative basis, at San Juan, Argentina; Camden, Australia; Huancayo, Peru; and Tonanzintla, Mexico. Overall technical supervision of the American program is under F. E. Roach, Central Radio Propagation Laboratory (CRPL) of the National Bureau of Standards at Boulder, Colorado, and E. R. Manring, Air Force Cambridge Research Center (AFCRC).

In the USNC-IGY program, recording photoelectric photometers automatically sweep the sky according to a definite schedule. The instruments record the principal line emissions of the nightglow in the three separate spectral ranges. Efficient coverage of the sky is obtained by observing around the horizon at different azimuths but at a fixed elevation, with additional sweeps at other elevations, and including one observation at the zenith. Scaling of intensities for a basic station network is accomplished at CRPL through use of a machine which transfers to punch cards readings from the pen and ink records of observed airglow intensities.

The punch cards are then fed into a computer, which applies a correction for light *scattered* into the photometer from the sky. The computer further corrects for the reduction of intensity owing to 'extinction' in the lower atmosphere, and for the apparent increase in intensity for observations taken at increasing angles from the zenith. This is accomplished very rapidly on a digital computer, which prints the corrected absolute intensities for the various locations observed in the sky.

The results are studied in part by plotting maps of constant intensity contours (isophotes) for a given region as deduced from a station's observations (see Fig. 2).

The computer is easily programmed to print numerical intensities correctly positioned in a circular area corresponding to the observed sky so that isophote contours can be quickly sketched in by hand.

The corrections made in reducing the raw airglow data require an estimate of the effective height of emission. Three methods

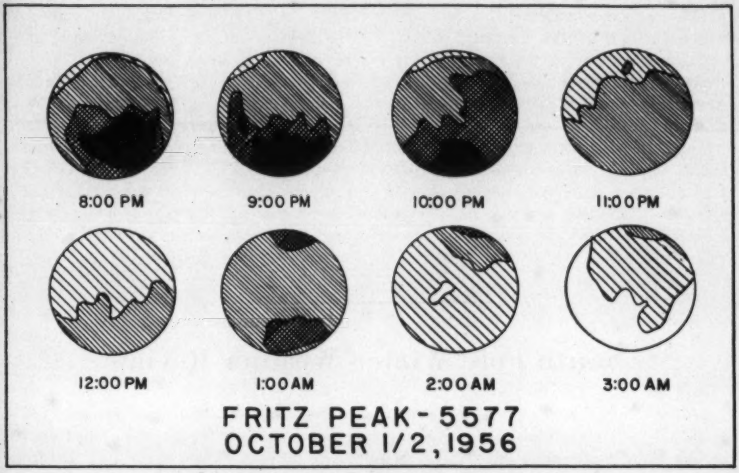

Fig. 2. *Circular Plots of the 5577Å Airglow Intensity in the Entire Sky as Observed at Intervals Throughout the Night of October 1/2, 1956, at Fritz Peak. Outer edge of each circle corresponds to a distance along the earth's surface of about 470 km from the observer, who is in the center of the circle. In preparing these isophote maps, the general increase of intensity toward the horizon has been eliminated.*

have been used: night firing of a rocket through the emitting layer, triangulation between two ground stations, and estimation by analyzing the increase of intensity toward the horizon. Attempts by all three methods lead to a 5577Å line emission height of 100 km, which is consistent with all the data.

The sodium emission layer has been observed at 85 km in a rocket experiment while the OH layer is probably situated at a somewhat lower level (near 70 km). A recent rocket experiment indicates that the red line emission at 6300Å originates above 160 km. This typifies the independent behavior of the oxygen emissions, despite their common transition level.

All airglow observers have noted the intensity variations of the airglow. Often the entire visible sky goes through synchronous variations, showing that the phenomenon is a large-scale one with a dimension of several hundred kilometers. On occasion, however, the various regions of the sky go through quite different variations during a night, as on October 1–2, 1956 (Fig. 2).

The photometric history of the airglow through an entire night is easily followed with the isophote charts mentioned above. The apparent movement of centers of airglow activity throughout the night suggests that the airglow is a dynamic phenomenon of the upper atmosphere. The physical significance of these complex changes is not known, but in a few cases, in which more or less discrete patches have been followed through successive isophote plots, the apparent velocity of motion is about 70 m/sec (150 mph). In general, the size of the large airglow features are of the order of 1000 km, while the temporal variations that occur seem to span several hours. Such motions may, of course, be due to progressive movements of excitation changes in the upper atmosphere, but it is interesting to speculate that they may indicate actual wind motions.

There is some evidence of a latitudinal-seasonal effect in the intensity of 5577Å radiation. Data from the Haute Provence Observatory, in France, and from three American stations suggest that a region of maximum activity exists at 38°N latitude (or at 44°N geomagnetic latitude), which might imply a possible secondary weak auroral zone. The question of such an apparent latitude maximum is complex, however, for there are additional seasonal variations as shown by observations at Fritz Peak. There the airglow is brighter to the north in summer and winter, but brighter to the south in spring and autumn.

In summary, it is apparent that airglow, originally thought of as a quiescent glow in the earth's atmosphere, is shown by current studies to be quite complex with dramatic temporal and spatial variations. The physical significance of these variations is not yet known, and this lack of knowledge is one of the compelling reasons behind the study of airglow during the IGY.

South Pole Winter Weather Review

A new record low surface temperature of −102.1°F was measured at the IGY Amundsen-Scott South Pole Station on September 17, 1957. This eclipses the previous low of −100.4°F, which occurred on May 11 of this year. During the intervening period, spanning from about mid-autumn to late winter in the Antarctic, South Pole temperatures fell below −95°F seventeen times.

The mean temperature at the South Pole throughout the past winter was −73°F; the maximum reached was −26°F. For 90% of the time during the long winter night, the temperature was below −58°F. The high mean wind speed of 16 mph, with peak gusts of about 53 mph, was unexpected; there were only 25 hours of calm weather during the entire winter. Snow storms, with very small crystals, occurred frequently.

The first 17 days of September comprised the coldest period of the winter at the South Pole, with an average temperature of −83°F, and for a four-day period, during which the record low was reached, temperatures never rose above −90°F. By September 25, however, the temperature had risen to −73°F, leading US Weather Bureau meteorologists to surmise that the coldest weather of the current season had passed.

Early in the Antarctic winter just ended, a long-range minimum forecast of −112°F (±3°) was made for the Pole. This forecast, made by Ron Taylor of the IGY Antarctic Weather Central, was based on available climatological data and empirical relationships.

Prior to the occupation of observation stations in Antarctica, it was thought by meteorologists that the mean monthly temperature at inland points would decrease rapidly after the setting of the sun for the winter. Later, it would continue to drop at a slower rate, possibly with some variation, reaching its lowest values at about the time the sun returned in the spring. This temperature regime was expected because it was felt that the strong mean westerly winds at all levels in the high latitudes of the Southern Hemisphere tended to inhibit meridional heat exchange, thus allowing radiational influences to be most effective on the perennially cold, high Antarctic continent.

However, past records from coastal stations show that following the initial rapid drop there actually tends to be a significant rise in mean monthly temperature, followed by another drop to the minimum monthly mean for the year late in the winter. That this unexpected feature of the temperature regime also holds for inland areas seems to be indicated by recent records from the IGY

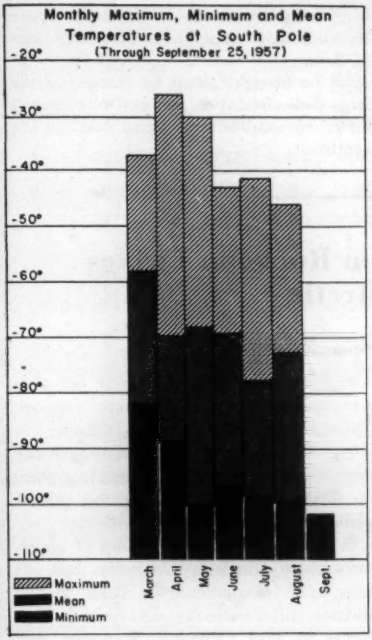

Fig. 3

Byrd and South Pole Stations. Many factors, such as cloudiness, wind velocity, or changes in the large-scale circulation pattern, may be responsible. It is hoped that data accumulated during the past Antarctic winter will provide an explanation.

At the time of the new record-low surface temperature, a pronounced temperature inversion prevailed in the atmosphere over the Pole. Just 30 feet above the surface, the temperature was 27°F higher, and at 1400 feet the temperature was 72°F higher. From about this level, temperatures decreased with altitude.

Such marked vertical temperature inversions are frequently found over polar regions but are accentuated over the South Pole because the dry atmosphere on the high polar plateau (the South Pole Station is at an altitude of 9200 feet above sea level) transmits outgoing heat radiation more readily than sea level atmosphere. Thus, the Antarctic continent, and the snow-laden polar plateau in particular, provide ideal conditions for the formation of vertical temperature inversions.

Prior to the IGY, the lowest temperature on record was −90°F, set in northeast Siberia in February 1933. This reading has already been exceeded a number of times at the US-IGY South Pole Station and at USSR inland Antarctic stations, but it is, nevertheless, of some interest to compare Arctic with Antarctic temperature lows. Other extreme lows recorded in the Arctic are −81.4°F, at Snag Airport, Yukon Territory, Canada, in February 1947—the lowest ever measured in North America—and −86.8°F, at a French station in Greenland, near the highest part of the icecap, in February 1950.

No record low temperatures are likely to be set, however, at the North Pole, where readings below −50°F are improbable. The most important reason for this is that the North Pole is surrounded by a very deep sea. The ice pack that covers most of the surface of the Arctic Ocean averages considerably less than 15 feet in thickness and is able to conduct heat to the atmosphere from the relatively warm and deep ocean below. The Antarctic, conversely, contains land masses far removed from ocean warmth, where great ice thicknesses can build up. A thickness of about 10,000 feet has already been measured at Byrd Station, in West Antarctica, and greater thicknesses are likely in the vast, high interior of East Antarctica.

It is possible that temperatures in the central interior of the Antarctic continent, nearer the "Pole of Inaccessibility," will be found to be even lower than those at the geographic South Pole. This area, where Soviet scientists hope to establish a station, is 4000 to 5000 feet higher than the South Pole and is farther from the sea and its modifying climatological effects. The Soviet Vostok I IGY Station, on the icecap at

72°08′S, 96°34′E, and only about 300 miles inland from the Davis Sea, has already reported a temperature of slightly below −100°F.

Local factors such as cloudiness and wind speed can cause monthly anomalies in temperature at individual stations. However, a significant rise in the mean winter time monthly temperatures over large areas of Antarctica, such as occurred this year, must be brought about by changes of the large-scale circulation patterns, causing a net influx of sensible and latent heat to the continent.

Preliminary Report on Rockoon Firings in the Arctic

During the period August 5–14, 1957, eighteen rockoon (balloon-launched rocket) flights were conducted as part of the US-IGY program by a team of scientists from the State University of Iowa under the direction of Dr. James A. Van Allen. The firings were made from the U.S.S. *Plymouth Rock* in the sea area bounded by Greenland, Labrador, Baffin Island, and Devon Island. These firings, which resulted in the first high-altitude magnetic measurements made within the northern auroral zone, constituted the summer-1957 phase of the IGY rockoon program of the State University of Iowa.

The operations plan called for firing of the rockoons between latitudes 55°N and 76°N. Extensive preparation, carefully coordinated with efforts of the Canadian IGY National Committee, and with essential assistance from the Inter-Service Support Coordinating Group for the US-IGY Rocket Program, culminated in the shipboard assembly of the necessary instruments and equipment.

Scientific equipment was installed aboard the ship during July. Included were eighteen Hawk rockets, thirty 20,000-cubic-foot balloons, a telemeter receiving station, eighteen auroral and cosmic-ray rocket instrumentations, and miscellaneous test equipment. The ship left Norfolk, Virginia, at noon on August 1, 1957, and headed for Thule, Greenland. The return date was August 20.

Scientific Objectives

High-altitude auroral, cosmic ray, and geomagnetic observations were planned. The scientific objectives were as follows:

(a) Investigation of total cosmic-ray intensity through and above the atmosphere in northern latitudes during the present period of maximum sunspot activity.

(b) Correlation of fluctuations of upper-atmosphere cosmic-ray intensity with (i) solar and magnetic data from ground stations, (ii) cosmic-ray data from balloon flights at Fort Churchill, Manitoba, and Minneapolis, Minnesota, and (iii) neutron monitor data at various ground stations.

(c) Investigation of the physical nature, energy, intensity, and latitude distribution of auroral "soft-radiation."

(d) Precise measurement of the absolute scalar magnitude of the total terrestrial magnetic field to altitudes of over 120 km in the auroral zone, using a proton precession magnetometer.

(e) Detection and measurement of atmospheric electrical currents in the auroral zone by the *in situ* measurement of discontinuities in the magnetic-field intensity.

(f) Correlation of high-altitude magnetic data with records from nearby ground magnetic observatories and with related geophysical phenomena.

Table 1. *Arctic Hawk Rockoon Flights*
August 1957

No.	Date (Aug.)	Balloon Release Time (UT)	Lat. N	Long. W	Experiment	Rocket Firing Altitude (ft)	Time of Firing of Rocket (min)	Duration Rocket Flight (sec)	Est. Peak Height (mi)	Results
1	5	1153	55°00′	54°00′	a, b, c	75,000	y + 89	N.K.	N.K.	Very weak telemeter signal
2	5	1658	56°37′	54°25′	d, e, f	N.K.	N.K.	N.K.	N.K.	Telemetering ceased at y + 47 min
3	6	1052	62°16′	56°17′	a, b, c	75,400	y + 81	318.4	72	Excellent data throughout
4	6	1603	63°56′	56°09′	d, e, f	75,000	y + 80	325	73	Good proton precession signals received
5	7	0328	67°20′	57°03′	a, b, c	—	—	—	—	Rocket did not fire
6	7	2204	72°55′	58°31′	d, e, f	—	—	—	—	Rocket did not fire
7	8	0717	75°12′	63°19′	a, b, c	74,000	y + 80	349	82	Good data throughout
8	10	0507	74°18′	63°34′	a, b, c	76,000	y + 82	327.4	73	Excellent data throughout
9	10	2336	72°04′	58°20′	a, b, c	75,000	y + 79	261.8	48	Good data throughout
10	11	0516	70°40′	57°00′	a, b, c	—	—	—	—	Rocket did not fire
11	11	2030	66°56′	54°56′	a, b, c	76,100	y + 88	336	76	Raw field data not yet analyzed
12	12	0748	64°14′	53°57′	a, b, c	—	—	—	—	Rocket did not fire
13	12	1355	63°03′	53°43′	d, e, f	76,100	y + 80	N.K.	N.K.	Telemetering signal ceased after rocket fired
14	13	0158	60°35′	49°16′	a, b, c	N.K.	N.K.	N.K.	N.K.	Electronic apparatus freeze-out at y + 50 min
15	14	0806	59°18′	47°48′	a, b, c	75,400	y + 78	N.K.	N.K.	RF transmitter failure at y + 7 sec
16	14	1350	57°44′	48°09′	d, e, f	74,700	y + 76.5	295	60	Poor data
17	14	2000	56°13′	48°46′	a, b, c	76,100	y + 79	284	55	Good data throughout
18	14	2251	55°40′	48°56′	a, b, c	72,500	y + 79.5	293.1	60	Excellent data throughout

CODE

a. Investigation of total cosmic ray intensity through and above the atmosphere.
b. Correlation of fluctuations of cosmic ray intensity with solar and magnetic data from ground stations.
c. Investigation of physical nature, energy, intensity, and latitude distribution of "auroral soft-radiation."
d. Precise measurement of the absolute scalar magnitude of the total terrestrial magnetic field using a proton precession magnetometer.
e. Detection and measurement of atmospheric electrical currents in the auroral zone.
f. Correlation of results from d and e with records from nearby magnetic observatories at ground stations.

N.K.: Not Known.
y: time of balloon launching.

Preliminary Results

Latitudes of launching ranged from 55°N to 75°N. Good scientific data were obtained up to 22 km during the balloon phase of thirteen of the eighteen flights; on seven of these, good data were obtained throughout the rocket flights as well. Peak rocket altitudes ranged from 77 km to 132 km. A brief report of the results follows:

(a) The total intensity of cosmic rays above the atmosphere at high latitudes is now approximately two-thirds of its value during the 1953–55 period. This intensity is nearly independent of latitude through geo-

magnetic latitudes ranging from 66°N to 86°N.

(b) Five new sets of data on auroral radiation were obtained. Its hardness was measured by a variety of absorbers. Preliminary indications confirm previous interpretations of this X-radiation to be typically of the order of 50 kev. One of these flights is of special interest as it was a night flight to an altitude of 97 km beneath a brilliant aurora that first became visible about ten minutes before the rocket fired. Intense soft radiation was observed by the rocket-borne equipment. A preceding daytime flight (only three hours earlier) showed little or no auroral radiation up to 81 km.

(c) A new magnetic electron spectrometer with a crystal detector was flown for the first time, reaching a maximum altitude of 87 km. No preliminary results are available.

(d) A miniature proton precession magnetometer was test-flown successfully. On a flight to 118 km on August 6, 1957, excellent magnetic intensity data, with an accuracy of five gammas, were obtained at two-second intervals. The data shows a discontinuity in precessional frequency corresponding to 800 gammas at an altitude of about 90 km on the down leg of the trajectory. However, it appears that the rocket spin correction, not yet applied, will account for this discontinuity.

Table 1 presents data on all eighteen rockoon launchings in this series.

The Special World Day Program for the IGY

The World Day Program for the IGY provides for the coordinated intensification of certain observations during periods when major solar-terrestrial effects are predicted. Regular World Days (RWD) and World Meteorological Intervals (WMI) were selected in advance of the IGY, keyed to appropriate phases of the moon, the occurrence of equinox or solstice, and the incidence of meteoric showers. These dates have been indicated in the IGY Calendar of Regular World Days (see *Bulletin*, No. 2, pp. 631–632). In addition, provision was also made for the rapid designation of Special World Intervals (SWI) on occasions of observed increases in solar activity of a character such as will probably be followed by magnetic, ionospheric, auroral, and perhaps cosmic ray disturbances in the earth's atmosphere.

During SWI, ionospheric vertical incidence stations increase their soundings from about every 15 minutes to every 5 minutes. Auroral observers are alerted for increased instrumental observations, and visual observers intensify their watches. Particularly important is the observation of auroras in low latitudes following the greater magnetic storms, and observers in these areas are especially vigilant during the SWI. Some cosmic ray experiments—such as balloon-borne experiments designed to detect cosmic rays of solar origin—are intensified for SWI. Rockets are held in readiness for firing during great magnetic storms, or as soon as possible after the onset of a flare. Solar astronomers also increase their observations during the SWI, particularly for experiments designed for better understanding of the solar eruption mechanisms.

A field station of the National Bureau of Standards, the North Atlantic Radio Warning Service (NARWS) located at Ft. Belvoir, Virginia, about 20 miles from Washington, was designated by the CSAGI as the IGY World Warning Agency (WWA). The World Warning Network is illustrated in Fig. 4.

NARWS had had considerable previous

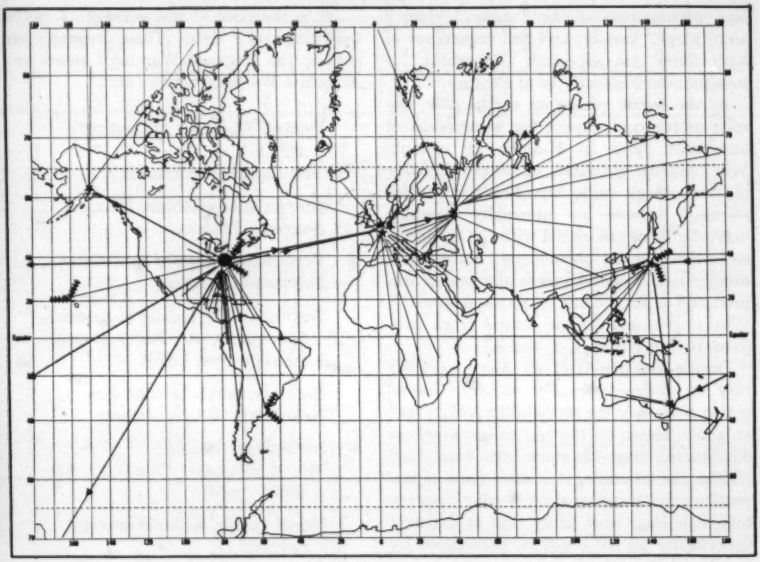

Fig. 4. *IGY World Warning Network. Circle represents World Warning Agency at Fort Belvoir, Va.; stars represent Warning Centers; clustered diamonds represent Radio Warning Stations. Map indicates in schematic fashion how Alert and SWI information is disseminated from the centers.*

experience forecasting ionospheric propagation conditions and was also engaged, with the cooperation of other such services throughout the world, in a study of the prediction of terrestrial solar disturbances.

The WWA examines solar data each day and receives advice from forecasting centers throughout the world concerning the probable solar activity in the coming day. Each day, shortly before 11:00 am EST, the WWA must make a decision as to the likelihood of imminent solar disturbances and related terrestrial effects, then issue the daily warning message at 1600 UT (11:00 am EST). Two kinds of messages are sent out on a day-to-day basis by the WWA: Alerts and SWI.

Alerts are called whenever solar activity is unusually high and significant geomagnetic, auroral, ionospheric, or cosmic ray effects are probable. The World Warning Agency utilizes certain criteria for judging the likelihood of impending solar-terrestrial effects, criteria that have been established empirically by past observations of solar astronomers and atmospheric physicists.

For example, an Alert may be declared whenever an unusually active sunspot region is on the solar disk, particularly when it is near the east limb of the sun, four or five days before it rotates towards a position near the center of the disk. The degree of activity of a particular sunspot region is judged by several kinds of observations of the region from the time of its appearance on the limb and during its transit across the disk. At the limb, observation of the intensity of emission of the yellow coronal

line, prominences of the "spray," "loop," and "surge" variety, and the occurrence of limb flares are especially important for judging potential activity of a region.

As the region passes on to the disk, the solar astronomers watch for occurrences of important flares in H-alpha or calcium light, unusual outbursts of radio frequency radiation, high radio flux levels or "noise storms," intense or unusually complex magnetic fields associated with the sunspots, and other similar phenomena. An Alert is usually not declared unless the region has produced a flare of at least importance 2. (The importance factor ranges from subflares to importance 1, 2, and 3.)

During the period of an Alert, an SWI may be declared, usually on eight hours' notice, whenever the probability is high that an active region on the sun will produce an outstanding magnetic storm with associated effects. For example, if a solar flare of importance 3+ is reported by a solar observatory, it is then most likely that at the next opportunity an SWI will be announced by the World Warning Agency.

The WWA receives advice in the early part of the day (all times mentioned are Universal Time or 0° Meridian Time) from observatories located at Moscow, Paris, Nederhorst in the Netherlands, Kokubunji in Japan, Anchorage in Alaska, Prague, Sidney, and Boulder, Colorado. At 1600 UT each day, a message is issued. Alerts commence upon receipt of the message and SWI, if called, commence at 0001 UT the following day; Alerts cease upon receipt of message, SWI at 2359 UT the same day. The messages are as follows:

Alert Starts X/1600Z
Alert Continues
Alert Finishes X/1600Z
SWI Starts Y/0001Z
SWI Continues
SWI Finishes X/2359Z and Alert Continues
SWI Finishes X/2359Z and Alert Finishes X/1600Z
No Alert
Alert Starts X/1600Z and SWI Starts Y/0001Z

(X is the date of the message; Y is the following day's date). These messages are sent to the Regional Warning Centers and Associate Warning Centers at:

Central Direction Netherlands P.T.T.
The Hague, Netherlands

Bureau Ionospherique Francais
Bagneux, France

Fernmeldtechnisches Zentralamt
Darmstadt, Germany

Institute of Terrestrial Magnetism, Ionosphere, and Radio Propagation Moscow, USSR

Radio Research Laboratories
Kokubunji, Tokyo, Japan

Ionospheric Station
Mount Stromlo, Canberra, Australia

North Pacific Radio Warning Service
Anchorage, Alaska

Williams Air Facility
McMurdo Sound, Antarctica

In addition, the messages are also fed into the international meteorological telecommunication circuits. Thus, rapid dissemination of the messages insures that most stations will be alerted in a matter of a few hours. Figure 5 shows the meteorological distribution scheme. Finally, radio messages of Alerts and SWI are broadcast by the National Bureau of Standards' Radio Station WWV in Morse code twice hourly, at four and 34 minutes after the hour, according to the following codes:

AGI—AAAAA State of Alert
AGI—EEEEE No state of Alert
AGI—SSSSS SWI will begin at 0001 UT following day
AGI—(Three long dashes) SWI in progress
AGI—TTTTT SWI terminates 2359 UT same day

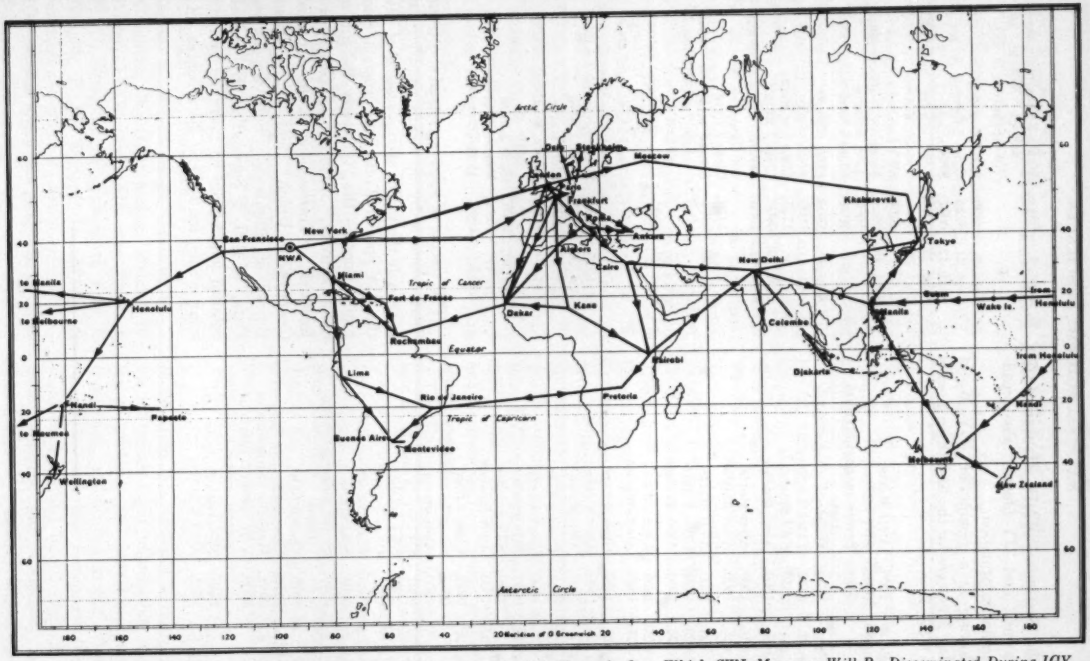

Fig. 5. *Map of the World Showing the Meteorological Telecommunication Channels Over Which SWI Messages Will Be Disseminated During IGY*

Radio Stations WWVH (Hawaii), LOL (Argentina), and JJY (Japan) also broadcast similar information.

Following is a resume of IGY World Warning Messages for the first three months of the IGY:

June 28,	1600,	Alert starts
June 30,	0001,	SWI starts
	04xx,	Severe magnetic storm starts
July 2,	01xx,	Magnetic storm finishes
July 3,	0722,	Class 3+ flare
	2359,	SWI finishes
July 6,	1600,	Alert finishes
July 16,	1600,	Alert starts
July 20,	1600,	Alert finishes
July 21,	1600,	Alert starts
July 23,	1324,	Class 3 flare
July 24,	1600,	Alert finishes
July 25,	1600,	Alert starts
July 27,	1600,	Alert finishes
July 28,	1346,	Class 3 flare
Aug. 2,	1600,	Alert starts
Aug. 7,	1600,	Alert finishes
Aug. 23,	1150,	Class 3 flare
	1600,	Alert starts
Aug. 24,	0001,	SWI starts
	2359,	SWI finishes
Aug. 25,	1600,	Alert finishes
Aug. 28,	0810,	Class 3 flare
	0913,	Class 3+ flare
	1600,	Alert starts
Aug. 29,	0001,	SWI starts
Aug. 30,	2359,	SWI finishes
Aug. 31,	1321,	Class 3 flare
Sept. 1,	9043,	Class 3 flare
Sept. 2,	0001,	SWI starts
	0316,	Severe magnetic storm starts
	1338,	Class 3 flare
Sept. 3,	1412,	Class 3 flare
Sept. 4,	06xx,	Magnetic storm finishes
	1300,	Very severe magnetic storm starts
	2359,	SWI finishes
Sept. 6,	1600,	Alert finishes
Sept. 7,	05xx,	Magnetic storm finishes (aurora visible in Washington, D. C.)
Sept. 9,	1600,	Alert starts
Sept. 11,	0245,	Class 3 flare
Sept. 12,	0001,	SWI starts
Sept. 13,	0046,	Very severe magnetic storm starts
	2359,	SWI finishes
Sept. 15,	06xx,	Magnetic storm finishes
	1600,	Alert finishes
	2040,	Class 3 flare
Sept. 18,	1305,	Class 3 flare
	1600,	Alert starts
	1725,	Class 3+ flare
Sept. 19,	0400,	Class 3 flare
Sept. 21,	1005,	Severe magnetic storm starts
	1340,	Class 3 flare
Sept. 22,	1344,	Second magnetic storm starts, superimposed on first
Sept. 23,	1600,	Alert finishes (aurora visible in Washington, D. C. and Mexico City, Mexico)
Sept. 25,	15xx,	Magnetic storm finishes
Sept. 26,	1907,	Class 3 flare
Sept. 27,	1600,	Alert starts
Sept. 29,	0016,	Severe magnetic storm starts
Sept. 30,	1675,	Class 3 flare
Oct. 1,	05xx,	Magnetic storm finishes
Oct. 2,	1600,	Alert finishes

This resume of solar-terrestrial effects and solar events is by no means complete but gives only the major events associated with the IGY Special World Day program. Such publications as the "Quarterly Bulletin on Solar Activity," "Journal of Geophysical Research," "Transactions of the American Geophysical Union," and the National Bureau of Standards' "Solar-Geophysical Data," (CRPL F Series, Part B), provide detailed information on magnetic activity, solar events, ionospheric disturbances, etc.

CSAGI Rocket and Satellite Conference

An international conference on rocket and earth satellite programs for the International Geophysical Year was held in Washington from September 30 to October 5. This was the first international conference on the IGY to be held in the United States.

The conference was called by the Special Committee for the International Geophysical Year (CSAGI), which asked the National Academy of Sciences to act as host. The conference brought together delegates from the various national committees participating in research rocket and satellite programs. The Chairman was L.V. Berkner, President of ICSU and CSAGI reporter on rockets and satellites. Hugh Odishaw, Executive Director of the USNC-IGY, was Chairman of the General Arrangements Committee.

The following is a list of official delegates who attended:

Australia: K. E. Bullen.

Canada: D. C. Rose, L. F. Smith.

Chile: Enrique Ortiz.

Cuba: Jesus Francisco de Albear, Luis Larragoiti.

Ecuador: Neptali Bonifaz, Carlos Castro, Alfredo Schmitt.

France: Lt. Gen. J. Guerin.

India: A. P. Mitra.

Iran: H. K. Afshar.

Japan: Takeo Hatanaka.

Peru: Jorge A. Broggi.

United Kingdom: Alastair Anthony, W. T. Blackband, J. G. Davies, H. S. W. Massey.

United States: W. Berning, G. M. Clemence, Michael Ference, N. C. Gerson, John P. Hagen, J. Hanessian, Joseph Kaplan, Homer E. Newell, Hugh Odishaw, W. J. O'Sullivan, W. H. Pickering, Richard W. Porter, J. G. Reid, Athelstan Spilhaus, W. G. Stroud, J. W. Townsend, Fred L. Whipple, P. H. Wyckoff. In addition, 49 scientists and engineers, active in the USNC-IGY satellite and rocket programs, served as delegates-at-large.

USSR: A. A. Blagonravov, A. M. Kasatkin, Sergei M. Poloskov.

CSAGI: Sydney Chapman, President; L. V. Berkner, Vice President and Reporter for Rocket and Satellite Programs; V. V. Beloussov, Member; M. Nicolet, Secretary-General; A. Day, Coordinator; A. H. Shapley, Reporter for World Days and Communications.

The conference opened at 10 am, September 30, with a plenary session, when status reports by the various national delegations were presented. The conference then divided into four Working Groups: Rocketry; Satellite Vehicles, Launching, and Tracking; Satellite Internal Instrumentation; and CSAGI Manual on Rockets and Satellites. These groups met at various times from October 1 through October 4.

A number of special papers on satellite vehicles, launching, and tracking, satellite ground-based scientific experiments, orbiting satellite devices and internal instrumentation, IGY rocketry program results, and IGY rocket research vehicles, techniques, and instrumentation were presented at special sessions.

The closing session of the conference was held at 10:30 am October 5. There was a brief description by A. A. Blagonravov of the Soviet satellite which had been launched on October 4. Conference resolutions were then presented. Dr. Detlev W. Bronk, President of the National Academy of Sciences, addressed the delegates, stressing the broad base of international cooperation which underlies the IGY program.

The resolutions, which were adopted unanimously, call for the prompt reporting of rocket firing data to World Data Centers on special rocket flight information summary forms developed and agreed on during the conference, within two weeks after each firing. The conference further resolved that there be a mutual interchange of rocket instrumentation and equipment and an interchange of personnel among countries participating in the IGY rocket program. The final resolution concerning rockets calls

for simultaneous launching of rockets on June 18, 1958, during a World Meteorological Interval.

Resolutions concerning the earth satellite program emphasized the need for additional visual and optical stations for satellite tracking, especially in higher latitudes, and for additional radio receiving stations providing tracking and telemetry reception at 108 mc/sec, 20 mc/sec, and 40 mc/sec.

The conference noted the possibility of using the facilities of existing ionospheric stations to receive satellite telemetered signals as well as the possibility of gaining interesting ionospheric data by means of radio amateur and volunteer observations of the Soviet satellite.

To implement the recommendation that additional telemetry stations be set up by research institutions and amateur radio groups, the conference recommended that both the US and the USSR provide advance data as to the forms of signals which they would transmit and that they also prepare articles about their systems to be disseminated to amateur radio groups.

The conference also recommended that the US and the USSR make arrangements for the rapid dissemination of information on satellite orbits and stated that it considered the exchange of publications, technical data, and scientific instruments pertaining to satellites highly desirable.

The need for coordination in content of transmitted positional and orbital data and consistency of basic constants and standards used in computation was also noted; the conference recommended that interested national committees meet in the near future to discuss these matters.

The final group of resolutions concerned the need for additional coordination on those items that could not be settled at the conference and recommended that special attention be given to the need for continued programs of scientific research utilizing instrumented rockets and earth satellites after the close of the IGY. To this end the conference recommended that countries undertaking such plans make information concerning their plans available as soon as possible.

NATIONAL ACADEMY OF SCIENCES

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IGY BULLETIN

A monthly survey by the U. S. National Committee for the International Geophysical Year. Established by and part of the National Academy of Sciences, the Committee is responsible for the U. S. International Geophysical Year program in which several hundred American scientists are participating and many public and private institutions are cooperating.

Volunteer Participation in the IGY Earth Satellite Program

The launching of the first artificial earth satellite on October 4, 1957, illustrated the importance of volunteer programs throughout the world for "acquiring" and tracking earth satellites and for the reception of telemetered data transmitted from them.

There are four distinct ways in which volunteers can contribute to the IGY Earth Satellite Program. First, they may join together in visual observation teams using relatively simple optical instruments. Second, they may establish radio tracking stations in conjunction with amateur radio clubs, universities or other scientific groups. Third, telemetry signals—scientific data transmitted by radio—from instrumented satellites may be recorded and forwarded to IGY centers for analysis. Fourth, volunteers may photograph satellite passages against the background starfield by means of high quality cameras and special techniques.

Visual Observation

The volunteer teams for visual observation are organized in a special program, called Moonwatch, established over a year ago under the auspices of the Smithsonian Astrophysical Observatory. To date, over 100 volunteer visual observation stations have been established within the US. Another 62 stations have either been established or are in the process of being established throughout the world in locations other than within the US or the USSR. Still another 66 stations are reported to have been established within the USSR as part of the Russian equivalent of Moonwatch.

The methods and instruments employed for visual observation of both US and USSR satellites are similar. Visual data are important for acquiring the satellites and for obtaining air density data in the final phase of each satellite's life. During this final period the satellite's batteries will probably have exhausted their power and the orbit parameters may be changing too rapidly to allow observation by precision tracking cameras. The wide coverage made possible by the visual program's many stations will therefore be of great importance. The observing methods of the Moonwatch program are detailed elsewhere in this issue of the *Bulletin*.

Radio Tracking and Telemetry Recording

The second and third types of volunteer participation, radio tracking and telemetry recording, are being handled through a recently organized program called Moonbeam.

Moonbeam preparations were made on the assumption that satellite transmitters would all utilize the 108 megacycle frequency for the transmission of tracking and telemetry signals. However, radio amateurs and scientific groups showed themselves remarkably adept in obtaining data on the first Russian satellites, which operated on 20 and 40 mc.

The primary system for tracking satellites by radio and recording their telemetry signals is the "Picket Fence" of Minitrack stations. However, material assistance will be given by the Moonbeam program, a supporting, secondary network of less elaborate stations operated by volunteer groups of scientists and radio amateurs.

The Moonbeam stations will be able to provide tracking data on the US satellite of sufficient accuracy to be of value for (1) acquisitional purposes, (2) possible resolution of small perturbations in the orbit due to localized gravitational anomalies, (3) supplementary data in case of premature failure of the transmitter or short life of the vehicle, (4) provision of additional data on the influence of the ionosphere upon radio signals.

In addition, the intervals of telemetered scientific data which may be recorded by these volunteer radio stations may prove to be particularly valuable (1) when the recorded interval coincides with a solar flare or other special occurrence, (2) in the event of failure of a data storage element in the satellite, (3) by providing a correlation check of time and position for the primary recording of data from those experiments using satellite-borne tape recorders, (4) for recording the time and circumstances of catastrophic damage to a satellite, should this occur.

Moonbeam will employ two tracking systems. The Mark II Minitrack system has been constructed by the Naval Research Laboratory and tested to demonstrate its suitability for use in radio tracking and telemetry. Another system, the Microlock, developed by the Jet Propulsion Laboratory of the California Institute of Technology for application to another telemetry system, is also adaptable to the radio tracking and telemetry of Minitrack signals from the satellite. These systems, both of which use phase comparison techniques and both of which are appropriate for construction and use by volunteer groups, will be described in later issues of the *Bulletin*.

General headquarters for the Moonbeam program are at the Naval Research Laboratory. The Jet Propulsion Laboratory is assisting and is maintaining a Moonbeam information office for the western United States. These offices are supplying technical information and consulting assistance to interested groups with regard to equipping, establishing, and operating stations in the Moonbeam volunteer radio network.

The American Radio Relay League (ARRL) has a position of active support in the Moonbeam program. Design, technical, and operational information concerning Minitrack Mark II, Microlock, and telemetry systems, as well as information on the Russian satellite radio system, is being provided to radio amateurs through *QST*, the journal of the ARRL.

The 20 and 40 mc frequencies used in the first Russian satellite were subject to much greater ionospheric effects than will be the 108 mc signal chosen for the US satellite. These properties make the 108 mc signal more valuable for precision tracking and the scientific experiments based upon it. The 20 and 40 megacycle signals are more useful for obtaining ionospheric data. At the September 30–October 5 CSAGI Conference on Rockets and Satellites, the United Kingdom delegation proposed a method whereby the vertical variation in the ionosphere above the F2 maximum might be deduced from volunteer radio observations of the USSR satellite. Similar plans for obtaining ionospheric information were already underway within the USSR.

Photographic Tracking

The fourth type of volunteer participation, photography of satellite passages against the background starfield, is a very recent development and has not yet been organized into a formal program. However, the USNC-IGY Technical Panel on the Earth Satellite Program has endorsed the efforts of the Society of Photographic Scientists and Engineers (SPSE) to organize its several local sections in the US for the purpose of obtaining photographs meeting these specifications: Negatives are to be 4″ x 5″, the minimum plate size to provide the requisite reading accuracy; they are to show the track of the satellite orbit against a fixed starfield background; and the trace of the satellite orbit is to contain a marker blank, or gap in the trace line, whose leading edge is timed to an accuracy of 0.1 seconds. The photograph is to be taken with a tripod-mounted camera located at a US Coast and Geodetic Survey Triangulation Station Marker (of which there are more than 100,000 in the US).

SPSE recommends that the timing blank be produced by placement of a dark slide over the camera lens, or by rapping the camera lens to displace the track, in coincidence with the timing signal from Radio Station WWV. More sophisticated means of timing, involving magnetic tape records or electro-mechanical devices, will undoubtedly be used in many cases, but opportunities for securing satellite traces with manually timed interruptions are not being overlooked.

HARVARD COLLEGE OBSERVATORY
ANNOUNCEMENT CARD 1374

Satellite 1957α — Since artificial earth satellites are short-lived astronomical bodies they should, presumably, be handled observationally and orbitally as are comets. As a tentative system of notation, pending IAU agreement, we shall identify each one by the year of its launching, followed by a letter of the Greek alphabet, to indicate successive order of launching. When more than one object is observable from one launching, a number shall follow the Greek letter in inverse sequence of brightness; the brightest component shall be α1, the next brightest α2, etc.

From press and radio accounts, Satellite 1957α was launched by the USSR during the night of October 3-4. Observations of only two components have been reported to the Astrophysical Observatory of the Smithsonian Institution. All estimates of brightness for α1 (both visual and photographic) give the second magnitude. Estimates of α2 range from the 4th to the 6th magnitude. From USSR reports of the satellite's dimensions, α2 is probably the radio satellite and α1 is the last rocket stage.

FIG. 1.

Experience of SPSE has indicated that the brighter of the USSR satellite bodies (1957 α1, the rocket shell) can be photographed at f/4.5 with films having an exposure index of ASA 200, when developed in D-19 for 5.5 minutes at 68°F. (Fig. 1 describes the tentative system of notation for artificial earth satellites suggested by Fred L. Whipple of the Smithsonian Astrophysical Observatory.)

SPSE reports that the fainter trace of USSR satellite 1957 α2 (the sphere itself) can be photographed at f/2.8 using a new superfast emulsion having an exposure index of ASA 1600. There is, however, some question as to the feasibility of obtaining technically acceptable negatives of satellite α2. In spite of the technical difficulties and equipment requirements for satellite photography, it is anticipated that an active and productive program is in prospect.

Plans for the US satellite call for an orbit observable from within a wide latitudinal belt, from 40°N to 40°S. Volunteer groups too far north or south to observe the first US satellite can, nevertheless, observe the USSR satellite, which was launched in an orbit inclined 65° to the equatorial plane and which is therefore observable from all the populated regions of the earth. Both the US and the USSR have announced their intentions to launch several satellites during the IGY.

Moonwatch Observing Methods

The National Academy of Sciences, assigned to the Smithsonian Astrophysical Observatory responsibility for the initiation of an optical tracking program for US earth satellites. A vital part of this program can be carried out only by a corps of qualified visual observers who, in organized groups, man selected strategic observing stations. The following information was adapted from the Bulletin for Visual Observers of Satellites, *which is prepared by the Smithsonian Astrophysical Observatory and printed by* Sky and Telescope.

The Observing Team

The basic principle of Moonwatch station organization is that there be a team of observers, each of whom maintains continuous watch (during the observing interval) of a specified sky area on the celestial meridian. These areas overlap so that the satellite cannot cross this "meridional fence" without being detected. This is the recommended arrangement to be used at least during the first observations for the acquisition of the satellite.

The Essential Data

In all problems of orbit calculation and analysis, the computing center will use the right ascension and declination of the satellite in the sky, and the time it occupied that position. These are the essential data of a successful Moonwatch observation.

For computing purposes, any one of several observing techniques might be used, and the satellite could be observed in almost any part of the sky. The results are reported to the computing center in whichever of the several systems of co-ordinates seems most convenient. The basic requirement is that the position be given to an accuracy of one degree of arc and the time to an accuracy of one second.

There are, however, certain practical advantages in narrowing the choice of methods. For instance, the desirability of establishing a meridional fence as the basis of any Moonwatch observing routine is well established. Since the US satellite's motion will be predominantly from west to east, when it does pass within range of a station it will almost certainly have to cross the meridian. It will, in fact, always reach its greatest height above the horizon and be in the best position for observation not far from the meridian. In the absence of more specific information about the satellite's orbit, the meridian is obviously the most profitable part of the sky to watch for the US satellite.

The time and position reported to the computing center, then, will always be determined at or near meridian passage. Next, how can the observations best be made?

Two Observing Techniques

Two basic methods used by astronomers to determine the position of a celestial body are the fundamental and the differential.

The fundamental method involves direct measurement by means of instruments such as a meridian circle. For example, as a bright star crosses the meridian, its declination can be found by measuring its altitude, while its right ascension is equal to the sidereal time of the meridian passage.

The differential method involves the measurement of differences in position, either on a photographic plate or with a telescope micrometer, between the object whose position is desired and nearby stars whose places are already known. Such techniques are used at observatories to find the position of comets and asteroids, and they will be used to determine the position of the satellite in the precision photographic tracking program.

Either of these two basic methods of the astronomer can be adapted to the needs of Moonwatch. The first method can be used if a marker is provided, either a mast or a

reticle, that accurately defines the meridian in the field of the observer's telescope (see Fig. 2). All the observer must do is give the time signal and note the satellite's position, as it blinks out behind the marker, in fractions of the field above or below the center.

Since the angular size of the field and the position of the telescope on the meridian will be known, the meridian altitude can be computed easily as soon as the satellite has left the field. It will be necessary to state whether the satellite passage was north or south of the zenith. The computing center, knowing the latitude and longitude of the station, can readily convert the meridian altitude of the observations into declination and the time into right ascension—the data that will be used in the electronic computer.

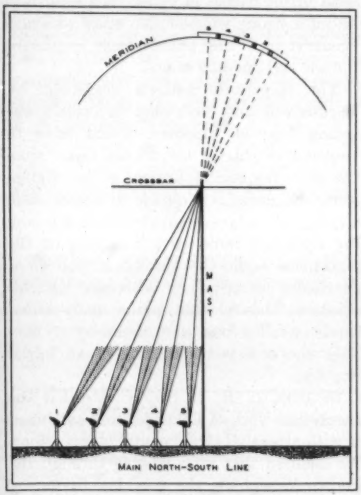

FIG. 2. IGY Moonwatch Station: main north-south line. Observing instruments are oriented relative to the junction of mast and crossbar. The upper part of the diagram shows the 12° fields of view of the instruments on the celestial meridian. The fields overlap about 1½° to prevent the satellite from crossing the "meridional fence" unobserved.

The second method, in its simplest form, makes use of star charts alone, without the aid of a meridian marker. The stars provide a background against which the position of the satellite can be determined at any moment during its passage across the field of the telescope. The accuracy of the observation may be considerably increased if the position is timed when the satellite passes close to a bright star or a prominent group of stars.

Therefore, it will be perfectly acceptable if a team of experienced observers decides to adopt the second method and eliminates the meridian marker entirely. This will obviate the work of erecting a mast or of inserting reticles in telescopes. The telescope field is unobstructed, with a consequent reduction in observer fatigue. Further details for those intending to participate in the program can be found in the *Bulletin for Volunteer Visual Observers* or by writing to The Smithsonian Astrophysical Observatory, 60 Garden Street, Cambridge 38, Mass.

Whistlers and Related Phenomena

Whistlers are naturally occurring audio frequency radio waves which, received on an antenna, amplified, and fed to a transducer for conversion into sound, can be heard as long descending whistles. They were first discovered in Austria in 1886, and in 1893 a report of some six years of investigation on them was published. Although this was overlooked until recently, the German scientist Barkhausen rediscovered them

while eavesdropping on Allied military telephone conversations during the first World War. Using a sensitive audio amplifier connected to a pair of separated ground rods, he recognized the phenomenon as a new one and called the descending tones "whistlers."

The observation of whistlers and related phenomena has great importance because of their potential usefulness in providing information about the very high atmosphere —the region above the level accessible to observation by ionospheric sounders. Whistler observations expanded in scope only when theory was developed to explain the origin and propagation of the signals themselves. Added impetus was given to an observational program when theory suggested that a complete experimental understanding of the nature of whistlers would provide new insight into conditions in the very high atmosphere. Observations had fortunately reached a stage ready for development into a broad synoptic program on the eve of the International Geophysical Year.

Development of Whistler Theory

The first advance in understanding whistlers came when Barkhausen and Eckersley independently suggested that the signals might arise from the propagation of sferics over long, dispersive paths. Sferics are transient radio waves arising from naturally occurring electric discharges in the earth's atmosphere. The most intense atmospheric discharges are lightning; nevertheless, all lightning strokes do not produce sferics. Through the work of A. G. Jean of the Central Radio Propagation Laboratory, National Bureau of Standards, at Boulder, Colorado, in cooperation with Stanford University, it is now known that there is a characteristic sferic wave form associated with whistlers and that it has a relatively low frequency of occurrence. Most whistlers are produced by sferics that are relatively rich in energy below 10 kc/sec. However, sferics with the usual energy spectrum peaking in the 10–20 kc region can produce whistlers if their total energy is sufficiently large.

Until recently there was still some doubt that lightning flashes generated whistlers, but this has now been resolved. On May 27 of this year, M. G. Morgan of Dartmouth College successfully observed a local storm with bright flashes in which each flash produced a strong whistler. No other whistlers occurred and the phenomenon continued for one and one-half hours.

The dispersive medium suggested by Barkhausen and Eckersley to explain the falling tone of whistlers, would have to transmit the higher frequencies faster than the lower frequencies present in the original sferic. Eckersley was unable to suggest such a path, but did point out that part of a very low frequency radio wave impinging on the ionosphere would pass through it with speed decreasing as frequency decreases. His calculations showed that paths many thousands of miles long were necessary to produce the observed spreading of an initial impulse.

In 1953, L. R. O. Storey extended the theoretical work of Eckersley and combined it with extensive experimental observations. He deduced that after passing through the known ionosphere, the very low frequency energy from a lightning flash is guided far above the earth and down again to the symmetrical point in the opposite hemisphere by the lines of flux of the earth's magnetic field. For the wave to be channeled along this path with the observed delays, an average electron density of about 400 electrons per cubic centimeter is required. Tentative theoretical explanations of the zodiacal light observed along the ecliptic constituted the only other basis for expecting such high electron concentrations at great distances from the earth.

Storey's deduction of the path of whistlers was given support in several spaced-station tests. A year-long correlation of whistlers at Stanford and Seattle confirmed the predicted localization of whistler energy. Sferics observed on the USS. *Atka* in the

southern hemisphere in 1954 were found to produce whistlers at Stanford. As expected, a three-year test at Achimoto (West Africa), on the geomagnetic equator, showed no whistlers.

In 1955, G. McK. Allcock of the New Zealand Dominion Physical Laboratory and H. W. Curtis of Dartmouth College conducted a coordinated experiment in New Zealand and at Unalaska at the opposite ends of a magnetic line of force. The results confirmed the occurrence of coincident whistlers having the expected relationships at the two ends of the path.

The importance of the whistler experiments is readily appreciated from the fact that the propagation time given by theory is approximately $\frac{D}{\sqrt{f}}$ for a very low frequency radio wave of frequency f traveling along the earth's field in the ionosphere. D, the dispersion, is proportional to the path length and to the mean value of the square root of the ratio of electron density to field strength. Typically, 5% of the total dispersion would result from the effect of the known ionosphere. Thus, models of the outer ionosphere can be inferred from experiment.

It has been found that whistlers are not observed at very high geomagnetic latitudes (the minimum strength of the earth's field is too low) or at very low ones (flux lines are too short to develop whistlers). Whistlers sometimes occur in trains of successive echoes. This is well illustrated in Fig. 3, which presents data from an Unalaska-New Zealand experiment. Note that here the dispersion increases by simple multiples, as expected.

IGY Whistler-Study Program

On the basis of the evidence sketched briefly above, the US-IGY whistler observational program was formulated. It includes two chains of stations for the observation of whistlers, and sometimes sferics, at frequencies up to 30 kc/sec. An eastern

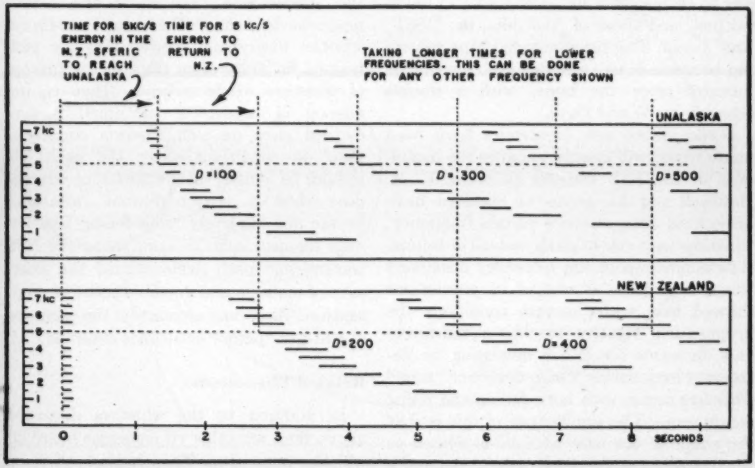

FIG. 3. Frequency and time of occurrence of whistler echoes between New Zealand and Unalaska, Alaska. Note that the dispersion, D, increases with increase in time. After Morgan, Annals of the IGY, v. 3, p. 315, 1957.

network under the supervision of M. G. Morgan of Dartmouth College includes stations at Thule, Greenland; Frobisher Bay, NWT; Knob Lake and Mont Joli, Quebec; Hanover, New Hampshire; Battle Creek, Michigan; Washington, D. C.; Bermuda; Gainesville, Florida; Huancayo, Peru; Cape Horn, Argentina (with the cooperation of Argentina); Port Lockroy, Antarctica (with the cooperation of the United Kingdom); and Ellsworth Station, Antarctica. A Danish station at Godhavn in Greenland is also coordinating its observations in this program.

A western network under the supervision of Robert A. Helliwell of Stanford University includes the following stations: College, Kotzebue, Unalaska, and Anchorage, Alaska; Seattle, Washington; Boulder, Colorado; Stanford, California; Wellington and Dunedin, N. Z. (with the cooperation of New Zealand); and Macquarie Island (with the cooperation of Australia).

Canadian stations are situated at Saskatoon, Ottawa, and Halifax. Other stations are to be operated by European IGY committees, and those of Australia, the USSR, and Japan. The recommended tape recording program is two minutes each hour at 35 minutes after the hour, with a double schedule on World Days.

Some recent new discoveries have been made which will greatly enhance the usefulness of the IGY whistler program. R. A. Helliwell and his group at Stanford have discovered that, above a certain frequency, whistlers may rise in pitch instead of falling. Re-examination of the Eckersley dispersion law and removal of one of its restrictions showed that under certain conditions the propagation velocity reaches a maximum and decreases for either increasing or decreasing frequencies. Thus, double or "nose" whistlers occur, with both falling and rising components. The significance of this is that the shape of the nose whistler is related to the intensity of the earth's field along the whistler path and gives information on the distribution of ionization as well. From this it is theoretically possible to place limits on the location of the path of propagation and, in addition, to obtain the distribution of ionization along the whistler path. With classical whistlers it would be possible only to determine the integrated value of the ionization over an assumed path of propagation. From nose whistler data the electron density is estimated to vary from several thousand per cm^3 at one or two earth radii to a few hundred at four or five radii.

As whistler phenomena have been examined more closely, other interesting phenomena have also come to light. Storey has noted that the detection of certain minor deviations from the predicted dispersion law would indicate the presence of hydrogen ions along the path. Work by K. Maeda, in Japan, has shown that the whistler path may depart markedly from the magnetic field-line path.

In January of this year, whistler mode echoes transmitted from NSS at Annapolis on 15.5 kc/sec were detected by the Stanford group at Cape Horn. Fig. 4 illustrates the transmission path along the earth's magnetic field line. The results confirmed whistler theory and showed that the path is open far more often than the occurrence of whistlers would indicate. That is, frequency of occurrence of whistlers may depend more on thunderstorm conditions than on conditions along the path. (It should be noted that whistler occurrence does show a strong diurnal variation.) Severe and relatively rapid fading together with frequent echo splitting along the NSS transmission path demonstrated the existence of multiple and unstable paths of propagation. These may account for the existence of whistler "pairs" sometimes observed.

Related Phenomena

In addition to the whistlers discussed above there are other vlf emissions heard on whistler apparatus. The simplest of these are the tweeks which last less than one-tenth of a second and are probably the re-

sult of transmission of sferic energy by successive reflection between the E layer and the earth over paths of different skip length. Other emissions such as hiss, constant tones, and the so-called dawn chorus of overlapping rising tones generally confined to the mid-audio range are not well understood. H. E. Dinger of the Naval Research Laboratory has studied periodic effects in the dawn chorus.

Recently a theory has been advanced by Roger Gallet and R. A. Helliwell to account for the unusual vlf emissions. It is based on selective amplification of noise energy already present in the medium. Energy for the amplification is provided by streams of ionized particles which come from the sun and travel along the lines of the earth's magnetic field. These streams are assumed to penetrate the ambient ionization of the exosphere with relatively little interaction. The mechanism of amplification is very much like that of traveling wave tubes. The velocity of the incoming particles must match that of electromagnetic waves in the medium to accomplish the transfer of energy from particles to waves which are then propagated to the earth. This theory is compatible with the suggestion that the exosphere may be "fibrous" as suggested by the NSS experiment. Even the dawn chorus may be explained by the theory if it is assumed that the ionized stream is bunched upon arrival.

M. G. Morgan has sought a correlation between vlf emissions and aurora since both are strongly correlated with geomagnetic disturbance; he reports that such a correlation is evident in every notable display of

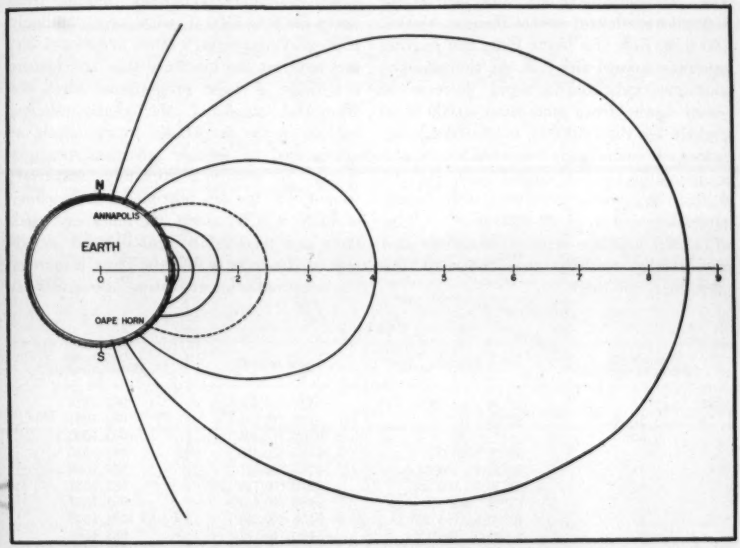

FIG. 4. Earth's dipole magnetic field for each 10° of geomagnetic latitude. Whistlers are believed to penetrate the ionosphere and follow the earth's magnetic field into the opposite hemisphere. Stippled zone is the known ionosphere; scale units are equivalent to earth's radii; dashed line is the path from Annapolis to Cape Horn.

flaming auroral rays. This appears to be consistent with the Gallet-Helliwell theory of vlf emissions.

An important part of the IGY whistler program will be the study of vlf emissions for the purpose of testing the traveling wave theory or developing new theories of their origin. These phenomena may provide a new way to measure the densities and velocities of solar streams. Plainly, the IGY whistler and vlf emission program promises to be a fruitful one in providing new knowledge of these emissions and of the atmosphere through which they travel.

Arctic Ocean Submarine Ridges

On August 12, 1957, geophysicists on IGY Drifting Station A, in the Arctic Ocean, reported that the ice floe on which the station is established had floated over a submarine ridge, or mountain range, rising more than 5000 feet above the ocean floor.

The feature was discovered in the course of a series of daily seismic depth soundings combined with gravimeter measurements. The two-mile-square floe was then about 850 miles north and west of Barrow, Alaska, 550 miles from the North Pole, and drifting generally toward the Pole. At the time the soundings indicated a rapid decrease in ocean depths, from more than 10,000 ft to slightly less than 5000 ft, increased gravity values correspondingly indicated substantial compensation in the crustal mass. As the station continued its northward drift, depths again increased to about 8000 ft.

Table 1 lists the series of soundings and raw gravity readings that indicated the presence of the ridge.

Although it was not possible to determine the length and width of the ridge on the basis of a single track, the fact that the gravity anomaly was first detected a full 60 miles from the point where the ridge was found suggests a major feature rather than an isolated one. For several days following the discovery, the station drifted westward, roughly parallel to the apparent trend of the ridge, obtaining soundings ranging from about 5000 to 5500 ft, with correspondingly high gravity readings. Two additional factors support the inference that the feature is a ridge of major proportions: First, the structural trend of the gently sloping bottom in the deep basin to the south, as determined by seismic reflection measurements, is also approximately east-west; second, for the sea bottom in the vicinity of 86°N, 125°W, about 300 miles eastward, there are recorded several isolated soundings on the order of 6000 ft. Thus, a more or less continuous linear feature about 5000 ft

TABLE 1

Hydrographic observation number	Location	Depth in meters	Uncorrected gravimeter reading
1	82°54′, 167°28′	3507 (11,506′)	983.1514
2	82°54′, 167°31′	3152 (10,341′)	983.1661
3	(?), 167°27′	3199 (10,495′)	983.1605
4	83°08′, 167°24′	3185 (10,450′)	983.1580
5	83°13.5′, 166°24,	3178 (10,427′)	983.1590
6	83°19.5′, 166°20′	3270 (10,728′)	983.1557
7	83°24′, 166°18	3186 (10,453′)	983.1557
8	83°36.5′, 166°15′	3156 (10,354′)	983.1548
9	83°39.5′, 166°12′	3106 (10,172′)	983.1547
10	83°48′, 167°01′	2968 (9,737′)	983.1739
11	83°52.5′, 167°50′	1656 (5,433′)	983.2060
12	83°52.1′, 168°38′	1571 (5,154′)	983.2121
13	83°51.5′, 168°43′	1515 (4,970′)	983.2118

high and trending generally east-west is indicated.

If the feature actually forms a continuous barrier across the Arctic, hydrographic studies should eventually detect a difference in the water masses on both sides. They will also provide a reliable estimate of the minimum depth to which the ridge forms such a barrier to the deep circulation. Temperature measurements made from Station A to depths of 10,500 ft south of the ridge and 6000 ft north of it indicate no difference in water mass down to the 6000-ft level. This means that the ridge does not form a continuous barrier above a depth of 6000 feet as the water mass on both sides of of it has evidently been equalized to that depth by movement through gaps in the ridge. Similar measurements made in the deeper water to the north will determine whether a continous barrier is formed by the lower portion of the ridge.

Although its topographic extent is uncertain, the new ridge appears to parallel the great Lomonosov ridge, which stretches from the northern coast of Ellesmere Island to the Soviet islands of Novosibirskiye Ostrova, dividing the Arctic Basin almost in two (see Fig. 5). The Lomonosov, discovered in 1948 by USSR scientists occupying similar drifting stations, is about 10,000 ft high. The deep soundings taken to the south of the position of the new ridge make it unlikely that it is a northward extension of the submarine peninsula known to trend north from the Chukchi Sea. (The Chukchi Sea reaches from the Bering Strait to the Arctic Ocean, between northwestern Alaska and Siberia.) There is a minor possibility, however, that the Chukchi Sea peninsula bears westward south of the region in which

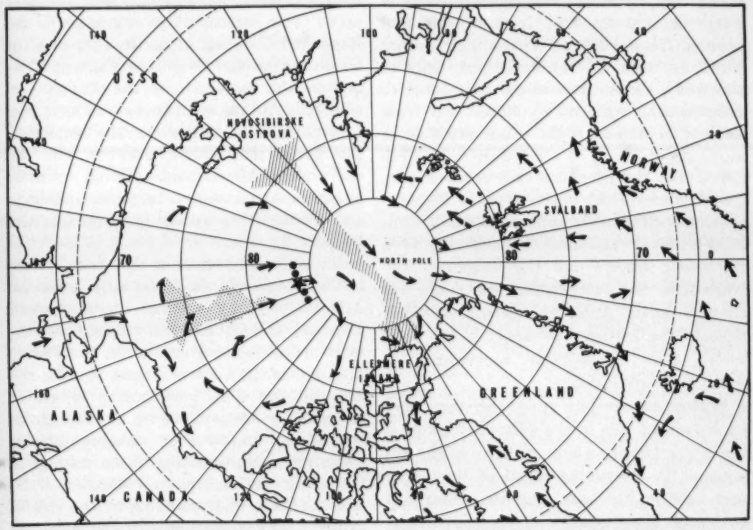

FIG. 5. Arctic Basin. Black star is IGY Drifting Station A at approximate position of newly discovered submarine ridge (black dots). Vertical pattern is Lomonosov submarine ridge; Stipple pattern is Chukchi submarine peninsula. Solid arrows are major known surface currents; broken arrows are major known subsurface currents.

the deep soundings were taken and then curves back to the northeast.

The team of scientists manning the station, then led by Maurice J. Davidson, are attached to the Lamont Geological Observatory of Columbia University. Their work is sponsored by the USNC-IGY and the US Air Force Cambridge Research Center.

Discovery of these submarine ridges and knowledge of their overall topographic dimensions and shapes is of great importance, particularly because of their strong influence on water movements. The overturn, mixing, and current flow of Arctic surface and subsurface waters must be known if we are to understand the mechanism of refertilization of the rich subarctic fisheries, the relationships between Arctic Ocean meteorology and oceanography, and the movement of the ice pack.

Most surface ocean currents are motivated both by winds and by differences in water density resulting from heating and cooling. Deep currents derive their energy primarily from density variations. Only in the Arctic Ocean does circulation occur to great depths with no significant aid from the winds. Although the winds are able to move the ice pack to some degree, it is believed that the ice exerts only a minor frictional effect on the water. Most of the Arctic Ocean circulation appears to result from level-for-level variations in density between the arctic waters and the waters of the Norwegian Sea, with which the major exchanges occur. Although current velocities beneath the ice may be weak, it has been shown that considerable movements of water mass are involved.

Bottom topography must, therefore, play an important role in the deep circulation of the Arctic Ocean, which, in turn, in the absence of the disturbing effects of direct contact between the wind and the water surface, must significantly influence circulation in the upper levels. The polar deep water is formed at depths of about 8000–9500 ft in the Norwegian Sea from which it flows into the Arctic Basin. Temperatures of −0.79° to − 0.91°C have been found at these depths near Svalbard, in the eastern part of the Basin.

In the Beaufort Sea, north of Alaska, however, bottom temperatures, at depths somewhat greater than 7000 ft, are as much as 0.50°C higher. To explain this differential, one investigator with the US Ski Jump project several years ago suggested the possible existence of a submarine ridge cutting the Basin in two. The later Soviet announcement of the discovery of the Lomonosov ridge confirmed this speculation.

Warmer Atlantic water flowing into the Arctic Basin sinks to intermediate levels in the Basin. It has been found north of the New Siberian Islands, near the "Pole of Inaccessibility" in the western part of the Basin, and at all Soviet stations near the geographic North Pole in a layer between depths of about 900 and 2350 feet. The cold north polar surface water originates in the Basin and flows out along the east coast of Greenland as the Greenland Current. Owing to the existence of the Lomonosov ridge, the Arctic Ocean appears to have two separate circulation systems: the system on the Pacific side flowing clockwise and the one on the Atlantic side flowing counterclockwise and involved in direct exchange and mixing with waters from outside the Basin.

An interesting effect of this dual system is that ice leaves the basin only from the Atlantic side, by way of the Greenland Current. Hence, the ice trapped in the more-or-less isolated system on the Pacific side is older and heavier than that on the Atlantic side. This phenomenon influences considerably attempts at ice forecasting for the Basin, and would probably greatly affect the overall pattern of ice wastage if the Arctic continues to grow warmer.

A complete understanding of the significance of submarine ridges in the Arctic in terms of their geological nature and origin, their effects on water mass differentials and circulation and, ultimately, on arctic and

subarctic marine life, as well as on the movement, accumulation, and ablation of the ice pack, will require considerably more data than are now available. By the end of the IGY, the cumulative efforts of US and USSR scientists on Arctic Ocean drifting stations may provide answers to these problems.

Oceanographic Island Observatory in Iceland

Some of the general objectives of the oceanography program were discussed in *IGY Bulletin No. 2, August 1957*. A worldwide study of sea level was included in the international IGY program in an effort to understand an observed cycle of mass deficiency between the northern and southern oceans depending on season. It has been observed from study of tide gauge records that the mean sea level in March is perhaps 20 cm lower than in September, for the Northern Hemisphere; the reverse is true in the Southern Hemisphere. In other words, sea level is lower in the spring.

Another observation gained from study of mean sea level is that there appears to be a mass loss in the northern hemisphere oceans between October and March. Walter Munk of Scripps Institution has estimated that the northern hemisphere oceans lose about 2×10^{19} grams of water while the southern hemisphere oceans only gain about 1×10^{19} grams. This mass difference corresponds to a sea level change of about 4 cm. There is so much uncertainty in this estimate, however, that the loss may be twice as much, or almost none at all.

The major objective of the IGY sea level program is, therefore, to obtain more reliable and accurate measurements for the values of mean sea level. Although there are about 500 tide gauges in operation throughout the world, there are many gaps, and few gauges are at islands or are located in the interior of water covered areas. About 200 to 250 new stations have been established for the IGY; the program is called Island Observatory Program because of the emphasis on island locations for the new stations, especially in the central oceanic areas. The southern hemisphere also was particularly lacking in tide gauges, and the continental coasts of this hemisphere are, therefore, the sites of many new stations.

One of the difficulties of computing mean sea level data from tide gauge records alone is the problem of distinguishing between mass changes and the volumetric changes. Accordingly, water samples are taken with simplified sampling bottles to depths of about 1000 feet. At the same time a bathythermograph is lowered to obtain a temperature profile. Using salinity measurements from the water samples combined with the temperature profiles, the densities can be computed and the apparent height of the water column reduced to a standard datum, allowing comparisons between oceanic areas of different temperature structures and salinities.

The location of many new tide-gauge stations at islands and coastal areas previously devoid of such instrumentation provides an opportunity for location of other instruments for a diversity of studies. Specially designed instruments have been installed at many locations to study the surface wave structure, from ordinary local wind waves with periods of a few seconds to waves of 15- to 20-minute periods caused by undersea earthquakes or perhaps generated by the great storms of the central oceanic areas. There is considerable transfer of momentum between atmosphere and oceans, as manifested by waves and surface currents, and recording microbarographs and microvariobarographs are in operation at many locations to provide atmospheric data along with the wave records in order to study the atmosphere-ocean coupling.

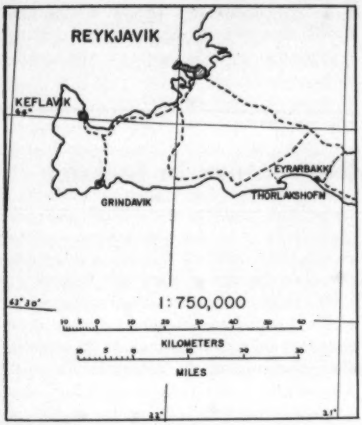

FIG. 6.

As an example of the newly established island observatories, Fig. 6 shows the location on Iceland of the tide gauge (US Coast and Geodetic type) at Grindavik and short- and long-period wave meters, thermograph, microbarograph, and microvariobarograph at Thorlakshofn. These instruments were installed by personnel from Lamont Geological Observatory with the assistance and cooperation of Icelandic scientists and authorities.

The location of the tide gauge at Grindavik presents some problems in analyzing the records owing to the nature of the harbor. Grindavik is a small fishing village; its harbor, called the *Hop*, is artificial and is connected to the sea by a narrow channel. The average tidal range inside the *Hop* is approximately 12 ft, and during the rising and falling tides swift currents flow through the narrow channel. It is estimated that there will be a phase lag between the sea and harbor tides of perhaps 10 to 15 minuntes and that harbor seiches, when they occur, will be of the order of 5 minutes in period.

Thorlakshofn is also a small fishing village, situated on a promontory which forms the southwestern shore of a large crescent-shaped embayment called Thorlakshafnarvik. Vessels as large as 5000 tons can tie up to the pier. The area is wide open to sea swell from the southeast to the southwest, and during stormy winter months waves often break over the concrete pier, which stands 10 ft above mean water level.

The short-period wave meter is installed at a depth of 30 ft, about 1000 ft from the end of the pier, while the long-period wave meter is installed at a closer location. Originally, both wave meters were installed 300 meters from the end of the pier at a depth of 30 ft. Subsequent failure of the long-period wave meter caused its removal and its later installation at a point closer to the end of the pier. Armored sea cable from the wave meters comes ashore at the seaward end of the pier, where it is connected to a telephone junction box; a lead-sheathed telephone cable connects the junction box to the shore recorders, at a distance of about 1500 feet. This type of installation was made necessary because wave action would have rapidly worn away the armor of the cable against the shingle and cobbles of the beach if the cable crossed the shore line at any other point.

At Thorlakshofn, the shore installation is located in a room adjoining the office of the local fishing company and consists of the recorders for both meters, a microbarograph, a thermograph, and will also contain the microvariobarograph. The short-period wave recorder, which has a flat response to waves of periods between 4 and 20 seconds, is pre-set to have full-scale readings corresponding to either ± 2 feet or ± 10 feet of water. The operator selects the appropriate sensitivity scale in accordance with local sea conditions.

The long-period wave meter has a maximum response to a period of 1000 seconds; it can resolve wave signals with amplitudes as low as a few millimeters of water. Temperature is also recorded on the chart in order to provide conveniently for the necessary corrections. A louvered outdoor shelter

houses the thermograph. Both wave meters and the microvariobarograph record on 35 mm film using a microfilm recorder that was adapted for this purpose.

Fig. 7 shows the kind of records obtained from the special instrumentation at the Island Observatories. The records were obtained at Iceland during tests of the installation; the three instruments were not operating concurrently. The upper record shows the short period waves ranging from ordinary wind waves with periods of a few seconds to wave trains of 15- to 20-second periods. The latter probably originated from a severe storm at some distance; they fall into the classification of "sea swell."

The middle record shows a sample from the long-period recorder, where short-period waves and the very long tide waves are filtered out. Temperature is recorded every half hour. This particular record shows the arrival of some small long-period wave trains; the gradual decrease in the record in the middle section is probably caused by that part of the tide which has not been filtered out.

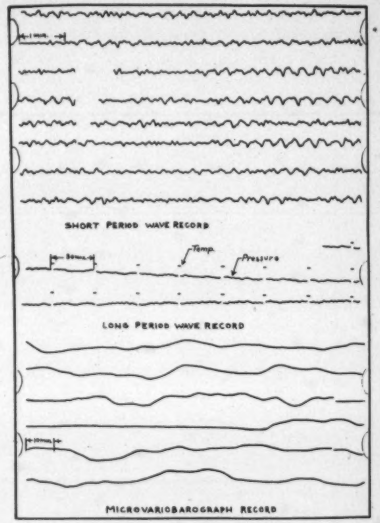

FIG. 7.

Examples of records from the microvariobarograph, which records the rate of change of the barometric pressure, are shown at the bottom of Fig. 7. This instrument indicates the passage of cold fronts and pressure changes associated with other meteorological phenomena.

The installation was made possible through the participation and cooperation of the Icelandic Harbor Administration (Vita-Og Hafnamalastjrinn), under the direction of Mr. Petur Sigurdson, and the fishing industry at Thorlakshofn (Meitilluim h.f.), Mr. Benedict Thorareuson, General Manager. The area for the sea installation was surveyed by the Icelandic Survey Vessel *Tyr* under the command of Mr. Gunnar Bergsteinson, and the wave meter assemblies were installed in the sea by the fishing vessel *M. B. Klengur*. Mr. Arni Benedictson is in charge of this cooperative station at Thorlakshofn, Iceland.

Second Soviet Satellite

The USSR launched its second satellite on November 3, 1957. The following descriptive text was issued on that date by Tass:

"In conformity with the International Geophysical Year program for studying the upper layers of the atmosphere as well as the physical processes and conditions of life in cosmic space, the second artificial earth satellite was launched in the Soviet Union on 3rd November.

"The second artificial satellite developed in the U.S.S.R. represents the last stage of the carrier rocket housing containers with scientific instruments.

"The second artificial satellite carries instruments for studying solar radiation in the short wave ultra violet and X-ray regions of the spectrum, instruments for cosmic ray studies, instruments for studying the temperature and pressure, an airtight container with an experimental animal (a dog), an air conditioning system, food and instruments for studying life processes in the conditions of cosmic space, measuring instruments for transmitting the results of scientific measurements to the earth, two radio transmitters operating on frequencies of 40,002 and 20,005 kilocycles (wave length of about 7.5 and 15 metres respectively) (292.5 and 585 inches) and the necessary power sources.

"The total weight of the apparatus mentioned above, the experimental animal and power sources amounts to 508.3 kilograms (1,120.29 pounds).

"According to observations the satellite has been given an orbital velocity of about 8,000 meters per second.

"According to calculations which are being verified at present by direct observations, the maximum distance of the satellite from the earth's surface exceeds 1,500 kilometers.

"The time of one complete circuit is about one hour, 42 minutes. The angle of the incline of the orbit to the plane of the equator is approximately 65 degrees.

"According to information received from the satellite, the scientific instruments and control of the life processes in the animal are proceeding normally.

"On 3rd November the second artificial satellite passed over Moscow at 7:20 A.M. and will appear again at 9:05 A.M.

"The signals of the satellite's radio transmitters on the 20,005 kilocycles are given in the form of telegraph beats lasting about 0.3 seconds with a pause of an equal duration. The 40,002 kilocycles transmitter emits continually."

Observations: Radio signals from the satellite were picked up early on November 3 by the RCA station at Riverhead, L. I., by the Naval Research Laboratory in Washington, by other government and private laboratories and by amateur operators throughout the country. Moonwatch observers and amateur astronomers in the Eastern states observed and photographed the satellite. Both visual observations and photographs showed a fluctuation in intensity of the light from the satellite, indicating that it was either tumbling or yawing.

Radio signals from the satellite ceased on November 10. On November 13, Pravda published a statement saying, "The program of scientific research connected with taking measurements in the second artificial satellite was planned for seven 24-hour periods. This program has now been completed. The radio transmitters of the satellite, as well as the radio telemetrical instruments on board the satellite have finished their work. Further observations of the second artificial earth satellite, for the purpose of exploring the properties of the upper layers of the atmosphere and forecasting its movements, are being made through optical means and radar."